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ABSTRACTS

1976 AFOSR CONTRACTORS MEETING

ON AIR-BREATHING COMBUSTION DYNAMICS

Held on   August 11 - 13, 1976   at

Air Force Aero-Propulsion Laboratory

Wright-Patterson AFB, Ohio

11 Aug 76

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IGNITION	PARTICLE DYNAMICS	FUEL AIR EXPLOSIONS
HOMOGENEOUS COMBUSTION	PREMIXING/PREVAPORIZING COMBUSTION	
HETEROGENEOUS COMBUSTION	CATALYTIC COMBUSTION	SUPERSONIC COMBUSTION
FLAME EXTINGUISHMENT	RAPID EXPANSION BURNING	EXTERMAL BURNING
COMBUSTION INSTABILITY	DETONATION	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
The report consists of a collection of abstracts of the numerous research progress reports given by AFOSR contractors and of invited papers from other governmental agencies and contractors. These papers presented over a three-day period composed the 1976 annual contractors meeting on air-breathing combustion dynamics. The principal investigators and their organizational association are also identified.

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AGENDA

1976 AFOSR CONTRACTORS MEETING
ON
AIR-BREATHING COMBUSTION DYNAMICS
AF AERO-PROPULSION LABORATORY
WRIGHT-PATTERSON AFB, OHIO
11-13 August 1976

11 August
Wed. AM

8:00	Bus - Motel to AFAPL	Holiday Inn - Dayton, Ohio
8:30	Official Registration	AF Aero-Propulsion Lab
8:55	Welcome - AFOSR	Dr. B. T. Wolfson (Program Manager) Dr. B. Quinn (Director) Aerospace Sciences Directorate (AFOSR)
9:05	Welcome - Military Host (AFAPL)	To be announced
9:10	Morning Chairman	Dr. B. T. Wolfson AFOSR Program Manager
9:20	Review of Airbreathing Combustion Research and Development Trends	Dr. H. Von Ohain (Chief Scientist) AFAPL
9:50	Injection, Atomization, Ignition and Combustion of Liquid Fuels in High-Speed Air Streams	Dr. J. A. Schetz Virginia Polytechnic Institute and State University AFOSR 74-2584
10:15	Mixing, Ignition and Combustion in Flowing Reacting Fuel+Air Mixtures	Drs. R. Edelman and P. T. Harsha R & D Associates F44620-75-C-0065
10:40	BREAK	
10:55	Research on Turbulent Mixing and Combustion - FY 76 Progress	Drs. D. E. Chriss, R. J. Schulz, R. P. Rhodes, C. E. Peters and M. L. Laster AEDC (ARO) (PO-0002-76)
11:20	In-House Research on Ramjet Combustion	Drs. R. R. Craig, J. E. Drewry and F. D. Stull AFAPL
12:05	Turbulent Mixing and Combustion in Reactive Recirculating Flows	Dr. M. Gerstein University of Southern California AFOSR 76-2876

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11 August
Wed. PM

12:30	Interaction of a Turbulent Jet with an Impinging Air Stream	Dr. P. Roy Choudhury and M. Lobell University of Southern California AFOSR 72-2400
12:55	LUNCH	

11 August
Wed. PM

2:00	Afternoon Chairman	To be announced
2:05	Application of Buoyant Bubble Flamespreading	Mr. George D. Lewis Pratt & Whitney Aircraft
2:30	Solid Fuel Ramjet Combustion Research	Mr. G. E. Jensen United Technologies Corp.
2:55	Modeling Solid Fuel Ramjet Combustion	Dr. David W. Netzer Naval Postgraduate School
3:20	BREAK	
3:35	Combustion Studies of Fast Flow Reactive Systems	Dr. R. Cookson Cranfield University, England AFOSR 74-2698
4:00	Combustion Studies in High Speed Reactive Flowing Systems at DFVLR	Dr. H. Eickhoff and G. Winterfeld DFVLR - Germany(In-House)
4:25	Research of Mechanisms of Supersonic Combustion and External Burning Relevant to U. S. Navy Requirements	Drs. R. C. Orth, P. J. Waltrup, R. T. Cusick and J. A. Schetz Johns Hopkins University N00017-73-C-4401
4:55	ADJOURN	
6:30	Social Hour (No Host Bar)	Officer's Club - WPAFB

12 August
Thurs. AM

8:00	Bus - Motel to AFAPL	
8:30	Morning Chairman	Dr. Austin W. Barrows Army Ballistics Research Laboratory Aberdeen Proving Grounds, Md.

12 August
Thur. AM

8:35	Review of Experiments Conducted by BRL in Fumer Technology	Drs. A. W. Barrows and J. R. Ward Army Ballistics Research Lab Aberdeen Proving Grounds
9:00	Base Region Combustion Phenomena	Dr. S. N. B. Murthy Purdue University BRL-DADD05-72-C-0342
9:30	Projectile Base Flow Control with Combustion	Drs. S. N. B. Murthy and J. R. Osborn Purdue University BRL-DADD05-72-C-0342
9:55	Injection Processes Associated with External and Base Burning	Dr. Klaus C. Schadow Naval Weapons Center
10:20	A Model of External Burning of Liquid Fuels	Drs. D. W. Harvey, B. R. Phillips, D. F. Hopkins and I. Catton McDonnell Douglas Astronautics Co. DASG60-75-C-0059
10:45	BREAK	
11:00	Turbulent Axisymmetric Base Flow Studies for External Burning Propulsion	Drs. J. E. Hubbartt, W. C. Strahle, and D. H. Neale Georgia Institute of Technology AFOSR 2794-75
11:25	Preliminary Evaluation of External Burning Propulsion	Dr. Mark Director Atlantic Research Corp.
11:50	Analytical Studies of External Burning Propulsion	Drs. C. E. Peters and T. V. Giel AEDC (ARO)
12:10	Flame Efficiency, Stabilization and Performance in Prevaporizing/ Premixing Combustors	Drs. S. L. Plee, M. B. Colket and A. M. Mellor Purdue University AFOSR 76-2936
12:35	LUNCH	

12 August
Thurs. PM

2:00	Afternoon Chairman	To be announced
2:05	Stratospheric Cruise Emission Reduction Program	Drs. G. M. Reck and L. A. Diehl NASA-Lewis Research Center
2:30	AFAPL Turbopropulsion Combustor Program Overview	Lt. Robert M. McGregor AFAPL (In-House)
2:55	Fundamental Modelling of Kinetics, Mixing and Evaporation in Combustors	Dr. J. Swithenbank University of Sheffield, England AFOSR 2682-74

12 August
Thurs. PM

3:20	**BREAK**	
3:35	**Mechanisms of Exhaust Pollutant and Plume Formation in Continuous Combustion**	Dr. G. S. Samuelsen University of California, Irvine AFOSR 74-2710
4:00	**Fundamental Combustion Studies Related to Air-Breathing**	Dr. F. A. Williams University of California, San Diego AFOSR 72-2333
4:25	**Combustion Modeling of Phenomena in Air-Breathing Combustion Engines**	Drs. H. J. Gibeling, H. McDonald and R. C. Buggeln United Technologies Research Center
4:50	**Experimental Investigation of Acoustic-Kinetic Interactions in Non-Equilibrium H_2-Cl_2 Reactions**	Drs. T. Y. Toong, J.-P. Patureau and C. A. Garris Massachusetts Institute of Technology AFOSR 74-2619
5:15	**ADJOURN**	

13 August
Fri. AM

8:00	**Bus - Motel to AFAPL**	
8:30	**Morning Chairman**	To be announced
8:35	**Research Needs in Alternate Fuel Combustion**	Dr. W. S. Blazowski AFAPL (In-House)
9:00	**Research Needs in Catalytic Combustion**	Capt. T. J. Rosfjord AFAPL (In-House)
9:25	**Assessment of Catalyst Technology for Catalytic Combustion**	Dr. J. A. Cusumano Catalytica Associates Palo Alto, Calif.
9:50	**Design Criteria for Catalytic Combustors**	Drs. J. T. Kelly, R. M. Kendall, E. Chu and J. P. Kesselring Acurex/Aerotherm
10:15	**Experimental and Theoretical Aspects of Hybrid Catalytic Combustion**	Drs. V. J. Siminski, A. E. Cerkanowicz, and H. Shaw Exxon Research and Engineering Co. F33615-75-C-2033
10:40	**BREAK**	

13 August
Fri. AM

Time	Title	Presenter
10:55	Mechanisms of High Temperature Catalytic Combustion	Dr. F. V. Bracco Princeton University AFOSR 76-3052
11:20	Research Needs in Combustion Diagnostics	Dr. W. M. Roquemore AFAPL (In-House)
11:45	Coherent Structures in Turbulent Flames by Laser Anemometry	Dr. N. A. Chigier University of Sheffield, England
12:10	Raman Scattering Measurements for Time- and Space-Resolved Data in Combustion Systems	Drs. M. Lapp and C. M. Penney General Electric Schenectady, N.Y.
12:35	LUNCH	

13 August
Fri. PM

Time	Title	Presenter
2:00	Afternoon Chairman	Dr. B. T. Wolfson AFOSR Program Manager
2:05	Aircraft Fire Protection Technology	Mr. J. R. Manheim and B. P. Botteri AFAPL (In-House)
2:30	Ignition, Combustion, Detonation and Quenching of Combustible Gas Mixtures	Dr. R. Edse Ohio State University AFOSR 73-2511
2:55	Ignition of Fuel Sprays by Incendiary Metal Particles	Drs. W. A. Sirignano and C. K. Law Princeton University AFOSR 76-3041
3:20	Executive Session (AFOSR Contractors and Grantees Only)	Dr. B. T. Wolfson AFOSR Program Manager
4:00	ADJOURN	

Review of Airbreathing Combustion
Research and Development Trends

Hans von Ohain

The technological trends of the various types of airbreathing propulsion systems will briefly be reviewed. The objective is to show the resulting stringent combustor development problems and associated basic research needs. Subsequently, a brief summary of APL's current program in the field of airbreathing combustion will be given.

INJECTION, ATOMIZATION, IGNITION AND COMBUSTION
OF LIQUID FUELS IN HIGH-SPEED AIR STREAMS

Joseph A. Schetz

Aerospace and Ocean Engineering Department

Virginia Polytechnic Institute and State University

ABSTRACT

This program currently has two main tasks involving, first, measurements of penetration, break-up and atomization of liquid jets in high subsonic and transonic speed air streams, and second, the ignition of liquid fuels in hot, supersonic airstreams. The progress in each area will be discussed separately below.

An extensive series of experiments on ignition of transverse liquid fuel jets in hot, supersonic airstreams using the new heated air facility was conducted during this time period. Detailed observations using the thermographic infrared camera were successfully obtained over a wide range of conditions. The maximum air temperature obtained in this first version of the heated air facility is 1650°F., and this proved insufficient to obtain unequivocal demonstrations of ignition in the flow field of interest. Therefore, a modification to the facility incorporating a combustion driven after heater, to raise the temperature from roughly 1600°F, to as much as 2500°F, has been designed and constructed. A first test series with the new combined facility has been completed. Vitiated "air" temperatures up to 2100°F were routinely obtained using the new after-burner. Tests with kerosene and CS_2 did not produce any clear evidence of auto-ignition in the vicinity of the injection port. We are proceeding to investigate a wider range of $\bar{q}$ in injection conditions.

The experiments concerned with penetration, break-up and atomization
of liquid fuel jets in high subsonic and transonic speed airstreams have been
proceeding rapidly. An extensive first-phase test program has been completed.
New and useful results on jet penetration and spread, as well as information
on detailed wave processes leading to break-up on the jets, have been obtained.
Drop size measurements have been successfully obtained, using 15 nanosecond
photomicrographs. A comprehensive technical report is in preparation covering
both phases of this work.

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MIXING, IGNITION AND COMBUSTION IN
FLOWING REACTING FUEL-AIR MIXTURES

R. Edelman and P. T. Harsha

R&D Associates
Marina del Rey, California

The goal of this program is the development of an analytical
model for the prediction of the performance of sudden expansion
burners as a function of the controllable parameters relevant
to combustor design. Because such combustors feature large
recirculation zones, the equations describing the sudden
expansion burner flow field are in general elliptic. The
development of numerical techniques capable of solving these
equations in flow fields in which large density gradients,
heat release and coupled finite-rate chemical kinetics must
all be included is a longer-term objective of this program.
For the near-term, however, the emphasis in this work has
been on the development of an approximate analytical technique,
termed the modular model.

In the modular concept, the flow field is divided into two
regions. The recirculation zone, treated as a stirred reactor,
is coupled to a parabolic boundary layer formulation for the
flow outside of the recirculation zone. Detailed hydrocarbon
oxidation kinetics and a turbulent kinetic energy formulation
for the turbulent shear stress are employed in the model de-
velopment. The coupling relations involve the gradients of
the velocity, temperature and species mass fractions along
the dividing streamline between the recirculation zone and
the directed flow, which define the inflow and outflow for
the stirred reactor. This coupling procedure is carried out
iteratively. Given a shape for the dividing streamline, an

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initial state for the perfectly stirred reactor computation
is assumed. This produces the values of the species mass
fraction and temperature at the dividing streamline which are
then used to provide boundary conditions for the parabolic
flow computation. The parabolic flow computation is carried
out, providing a new estimate for the feed rates to the
stirred reactor, which in turn allows a new stirred reactor
state to be computed. The process is iterated until changes
in the parameters describing the state of the recirculation
zone are small.

Effort during the current period has centered on the develop-
ment of the parabolic flow model. This has involved combining
the general parabolic reacting flow analysis of Boccio,
Weilerstein and Edelman [1] with the turbulent kinetic energy
model developed by Harsha [2]. To test the combined analysis,
calculations of a reacting hydrogen-air jet have been carried
out and compared to experiment [3], with excellent results.
Current work is now aimed at expanding the chemical system
involved in the computation, and reducing the computational
time required through the use of automated matrix shrinking
procedures and the reduction of the member of active species
computed through the use of element conservation equations.

References

1. J. L. Boccio, G. Weilerstein and R. B. Edelman, A Mathe-
    matical Model for Jet Engine Combustor Pollutant Emissions,
    General Applied Science Laboratories, NASA CR-12120B,
    GASL TR-781, 1973.

2. P. T. Harsha, A General Analysis of Free Turbulent Mixing,
    Arnold Engineering Development Center, AEDC TR-73-177,
    1974.

3. J. H. Kent and R. W. Bilger, Measurements of Turbulent Jet
    Diffusion Flames, Chales Kolling Research Laboratory,
    University of Sydney, Technical Note F-41, October 1972.

RESEARCH ON TURBULENT MIXING AND
COMBUSTION - FY76 PROGRESS[1]

D.E. Chriss[2], R.J. Schulz[2], R.P. Rhodes[2],

C.E. Peters[2], M.L. Laster[3]

The objective of this research is the development of reliable and physically perceptive analytical models for the turbulent mixing and heat release mechanisms in turbulent combustion systems. The approach taken in this theoretical and experimental study is to develop analytical models for the particular flow processes, then to conduct detailed experiments in order to verify and refine the models. Major emphasis is placed on the development of adequate models for (1) the turbulent transport properties for momentum, energy and mass in a variety of free and confined mixing systems, including flows with chemical reactions and with recirculation, and (2) the interaction of heterogeneous turbulent mixing and finite rate chemical reactions.

During FY76, the study was concerned with ducted flows with imbedded recirculation regions, such as are found in sudden expansion, or dump, combustors. The experiments on ducted nonreactive hydrogen-air flows, which were completed in FY75, were analyzed and compared with the predictions of the modified Imperial College elliptic numerical analysis. Serious deficiencies in the elliptic analysis were found for the flows of interest, and the analysis is not suitable for systematic evaluation of turbulent transport models for variable density recirculating flows. A report describing the results of this study of variable density recirculating flow was prepared and is in the publication cycle.

The series of experiments on ducted reactive hydrogen-air flows with recirculation was continued. Measurements of pitot pressure and hydrogen element mass fraction are made with probes, and measurements of instantaneous and mean velocities are made with a laser velocimeter (LV). Preliminary LV results showed that there were insufficient natural particles in the flow to provide an acceptable data rate. Therefore, the combustion apparatus was modified to facilitate seeding with one-micron aluminum oxide particles. Window contamination problems in the reactive tests were resolved, and LV velocity measurements in the reacting flow have been made. The LV results indicate very large temporal fluctuations of the velocity in the recirculation region.

Development of the Rhodes turbulence-chemistry interaction (TCI) analysis for ducted flows with recirculation continued. At present, the chemistry in the reverse flow region is assumed to be in equilibrium. (The TCI analysis for nonrecirculating flows, which was developed earlier in this project, has been applied this year to the analysis of low altitude rocket plume experiments; these experiments were carried out at the AEDC under AFRPL/AFFTD sponsorship.)

During FY7T/FY77, the reactive hydrogen-air experiments will be continued, with emphasis on the LV measurements at various stoichiometries. To date, the experiments have been carried out in an apparatus with a duct to jet diameter ratio of ten; this is about the upper limit of duct/jet diameter ratio for practical applications. The apparatus will be modified to provide a duct/jet diameter ratio of two, which is near the lower limit for practical dump combustors. Development of the TCI model for flows with recirculation will be continued, with emphasis on an adequate formulation for the concentration field in the reverse flow region.

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RESEARCH ON TURBULENT MIXING AND
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D.E. Chriss[2], R.J. Schulz[2], R.P. Rhodes[2],

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continued, with emphasis on an adequate formulation for the con-
centration field in the reverse flow region.

-2-

In-House Research on Ramjet Combustion

Air Force Aero-Propulsion Laboratory

R. R. Craig, J. E. Drewry and F. D. Stull

Dump combustors have become the basis of modern volume limited ramjet missile designs. Such combustors do not contain combustor cans for flame stabilization and must depend to a large extent upon recirculation zones formed by a sudden area change. Although many such combustors have been successfully built and tested over the past several years, the specific nature of these prior designs have precluded obtaining a sound technical data base or detailed flow-field data necessary for combustor modeling. The objective of in-house programs being conducted by the Ramjet Engine Division is to provide such a data base for the development of compact ramjet combustors having wide ignition limits and high combustion efficiencies over a wide range of flight conditions.

In one of these efforts involving the Room 18 Combustor Thrust Rig, an investigation was conducted extending previous small scale (2" to 5" D) dump combustor overall performance data to larger combustors (8" to 12" D) maintaining "pressure scaling" criteria. A parameter study was then conducted around the 12" baseline configuration, with and without flameholders, in which combustor length-to-diameter (L/D), combustor length-to-step height (L/h), characteristic length (L*), fuel injector type, inlet temperature and chamber pressure were varied. Lean blowout limit, combustor efficiency and combustor pressure drop were obtained for these runs using JP-4 fuel. A limited number of additional tests were conducted with Shelldyne-H fuel. Results obtained from this program are summarized below:

Pressure scaling may be applied (with caution) to dump combustors without flameholders. Combustor performance with flameholders does not appear to scale, with the larger combustors achieving higher combustion efficiencies than the smaller combustors. In addition, pressure drops are much higher in small scale combustors where larger blockages are required for flame stabilization.

In general, the addition of flameholders to short L/D dump combustors increases performance substantially and tends to reduce differences caused by single variations in dump combustor geometry and operating conditions.

Combustor length-to-step height (L/h) appears to be a more important parameter in dump combustors of varying dump ratios (A_2/A_3) than combustor length-to-diameter (L/D).

JP-4 and RJ-5 fuels give comparable combustion performance except at low inlet temperatures (750°R) where RJ-5 performance decreases rapidly with high fuel-to-air ratios.

Combustion efficiencies measured in premixed dump combustors without flameholders show that combustor L/D has a strong influence on performance at lean fuel-to-air ratios and a much smaller influence at near stoichiometric fuel-to-air ratios. Fuel injection near the dump section can greatly overshadow this effect by maintaining the combustor recirculation zone at a near stoichiometric fuel-to-air ratio.

In another effort involving the Building 450 Combustion Test Facility, basic flowfield studies were conducted on a 4" D dump combustor (L/D = 3.9) under cold flow conditions. These studies included surface flow visualization, pressure probing and gas sampling within a representative combustor duct. Flow visualization tests, which were performed using a surface oil flow technique, graphically demonstrated the complex nature of the flow recirculation/reattachment region downstream of the dump station. Detailed measurements of wall static pressure, flow static pressure and flow total pressure were made for the combustor flowfield. Gas concentration measurements of simulated fuel (argon)/air mixing were made in the combustor duct using a unique on-line, real-time gas sampling/analysis system. Results obtained from this program are summarized below:

Very accurate measurements of the recirculation zone length were obtained using the surface oil flow technique. Correlation of this data, along with other available results, in terms of step height produced empirical relationships for the prediction of recirculation zone length.

The detailed measurements of wall static pressure, flow static pressure and flow total pressure in conjunction with the flow visualization results provided a more complete characterization of the overall combustor flowfield, showing four distinct flow regions. It was also observed that the flow reattachment point could not be realistically correlated with wall static pressure.

On-line, real-time gas sampling utilizing a quadrupole mass spectiometer, provided detailed mixing profiles for argon being injected through eight wall orifices into the inlet air flow. The effect of fuel injector pressure on jet penetration and downstream mixing was determined for several pressure levels.

Future research plans and needs in the ramjet combustion area will be discussed.

References

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3. Drewry, J. E., "Characterization of Sudden-Expansion Dump Combustor Flow-fields", AFAPL-TR-76-52, in publication.

4. Craig, R. R., Buckley, P. L., and Stull, F. D., "Large Scale Low Pressure Dump Combustor Performance", AFAPL-TR-76-53, in publication.

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TURBULENT MIXING AND COMBUSTION
IN REACTIVE RECIRCULATING FLOWS

by

Melvin Gerstein
University of Southern California
Mechanical Engineering Department
Los Angeles, California 90007

It has been shown that a spray in vortex flow follows a substantially different path than the gas. This deviation leads to changes in the local air/fuel ratio and changes in the efficiency and stability of combustion. The turning of the flow also causes impingement of the fuel on the combustor wall. The behavior of the spray hitting the hot surface also has a major effect on the efficiency and stability of combustion.

In order to establish the nature of the spray-wall interactions, experiments have been conducted with a variety of fuels hitting a heated surface. The nature of carbon formation on the surface was reported previously. The vaporization rate is reported here.

Three zones of behavior are identified which parallel the zones identified in liquid heat transfer but significant differences exist.

In the first zone, the liquid wets the wall and evaporates from the surface. Since this study deals with spray impingement rather than massive liquid films, the fuel

quickly comes into temperature equilibrium with the surface. The rate of vaporization is controlled by the vapor pressure of the fuel and not by heat transfer in this region.

The second region is a transition region from surface vaporization (region I) to film vaporization (region III). This transition region (region II) is very dependent on both liquid and surface properties. The onset of transition can be moved to higher temperatures by the use of additives or to lower temperatures by changes in fuel and surface properties.

The third region is a region of vapor phase vaporization and, once suspended, the drop lifetime is independent of surface properties but is strongly dependent on the heat transfer rate from the surface to the drop. Since surface deposits affect the lifetime of the drop, there is an effect of surface coating on drop lifetime. The distance from the surface to the drop affects the heat transfer rate so that drop size at the time of lifting affects the drop lifetime. This is also a region of unstable or oscillatory vaporization - the surface to drop distance fluctuating with time. If the amplitude increases, the drop strikes the surface and shatters.

INTERACTION OF A TURBULENT JET WITH AN
IMPINGING AIR STREAM*

P. Roy Choudhury and M. Lobell
University of Southern California
Los Angeles, California 90007

The objective of this program is to study the interaction of vortices induced by a sudden expansion step and a cross-jet located in the vicinity of the step. In a combustor, the cross-jet acts as a fluid amplifier giving rise to a variable strength flame holder with a significantly larger flame spreading. In addition, the cross-jet is able to smooth out rough burning under certain geometric and operating conditions. Previous work at the University of Southern California has shown the feasibility of effectively using a cross-jet in the vicinity of either a bluff-body or a sudden expansion flame holder.

In order to better understand the mechanism involved, the following facets of the program were studied during the last fiscal year.

a) Pressure-time histories of rough burning in volume-limited burners with different nozzle locations and discrete cross-jets.

b) Spectral intensity of pressure fluctuations for both cold and hot reacting flows over a sudden expansion step.

c) Cold flow studies of the effect of cross-jets on the size of the recirculation zone downstream of the step.**

d) Overall system pressure loss with an air-jet as compared to a stream-lined bluff body flame holder with similar flame spreading.

The following conclusions can be reached from the study during the past year.

1. Rough burning in a sudden expansion burner is initiated by the flip-flop motion of the shear layer emanating from the edge of the step. Such motion alternately strengthens and weakens the recirculation zone and perturbs the system. When the shear layer either overshoots or undershoots the edge of the nozzle, the roughness seems to disappear.

2. The spectral intensity of pressure fluctuations show that, on the average, the increase in intensity over the cold flow is within a frequency range of 10 to 300 Hz. These values were independent of the changes in resistance in the air and fuel lines. The larger characteristic times associated with this low frequency range are typical of heat transfer rather than chemical kinetics.

3. The interaction of the vortices induced by the cross-jet and the sudden expansion step causes a large increase in the size of the recirculation zone which literally engulfs the nozzle edge and smooths out rough burning.

4. A combustor with cross-jets consisting of discrete holes has a lower overall pressure loss compared to a streamlined bluff body with similar flame spreading.

An integral method is being developed to explain and correlate some of the experimentally observed phenomena such as the amplification of the recirculation zone caused by the cross-jets.

The program for the present fiscal year involves further work in a more realistic axisymmetric combustion chamber with discrete air jets rather than slot jets used earlier. In addition to the system characteristics and performance, the scale effects will also be investigated.

Application of Buoyant Bubble Flamespreading

by George D. Lewis

Pratt & Whitney Aircraft - Government Products Division

The ability of centrifugal force to greatly accelerate normal
flamespreading rates was demonstrated in a combustion centrifuge.
Values in excess of four times turbulent flamespeed were measured.
In addition, the independence of the flamespreading process from
pressure (down to 5 psia) and temperature (down to -100°F) effects
was shown. A basic theory evolved and a mathematical model was
developed. The new flamespreading principle was applied to a
full size afterburning engine and a motion picture comparison
of a conventional and a swirling flow augmentor is presented.

SOLID FUEL RAMJET COMBUSTION RESEARCH

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Chemical Systems Division

The combustion research on solid fuel ramjets has stressed three principal areas: flameholding, fuel regression rate modeling, and combustion efficiency enhancement.

Flameholding investigations focused attention on defining the geometric factors of the combustor entrance and aerodynamic properties of the entering air stream. Results of these studies were applied to selection of air injector configurations which achieved stable combustions at low values of port-to-throat and port-to-injector area ratios.

A fuel regression rate expression based upon a turbulent boundary layer diffusive process with fast kinetic was developed. Refinement of the burning rate expression included (1) coupling the fuel regression rate with the core flow acceleration to account for the axial variation of the regression rate and (2) incorporation of a radiative term to account for effect of combustor size. Low pressure data (<30 psi) fall below the derived expressions. Transient heating analysis did not completely account for the difference and therefore, the low pressure regression behavior may be kinetically controlled.

Combustion efficiency studies concentrated attention on development of a reliable correlation expression which accounts for the effect of operation over a wide range of equivalence ratio, mixer length, and injector area ratio. The effect of grain geometry and split air flow combustor configuration were also evaluated.

ABSTRACT

MODELING SOLID FUEL RAMJET COMBUSTION

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A model is needed for solid fuel ramjet combustion which is capable of predicting the effects of design and operating variables on the fuel regression rate, combustion efficiency, and flammability limits. During the past two years experimental and theoretical studies have been conducted at the Naval Postgraduate School with the primary purpose of developing such a model. Until recently the model has had quite limited capabilities. Recently, improvements have been made in the turbulence modeling and in the techniques for obtaining numerical stability which have significantly improved the predictive capability of the model. The model predicts a fuel rich recirculation region, an inlet flame pattern, and a distribution of turbulence intensity which are in good agreement with experiment. In addition, fuel regression rates and patterns as a function of air flow rate are predicted which are also in good agreement with experiment. Diffusion rates in the boundary layer development region are currently predicted to be higher than has been found experimentally. Current work with the model includes combustion efficiency predictions, improvement of the predicted downstream diffusion rates, and the affects of aft-end mixing. Basic assumptions of the model, the solution technique, predictive capabilities and weaknesses will be discussed.

Combustion Studies of Fast

Flow Reactive Systems

by

Dr. Roy A. Cookson

ABSTRACT NOT AVAILABLE

Studies on Turbulent Exchange
in Diffusion Flames (DFVLR)

Dr H Eickhoff and Dr. G. Winterfeld

Present investigations concern the determination of
turbulent transport coefficients of momentan mass and
energy. This is performed in two different ways. First
by calculating the effective transport coefficients from
the time mean balance equations inserting into these the
measured profiles. As this is of some uncertainty, with
these coefficients as a first approximation, the time mean
transport equations are solved simultaneously by a finite
difference method. Here, transport coefficients are chosen
so, that the calculated profiles of time mean values of
velocity and concentration are in accordance with measured
profiles. The transport coefficients are empirically connected
with overall characteristics of the flow system by simple
algebraic expressions.

In this way, free burning hydrogen-air diffusion flames with
different initial conditions are investigated, where unmixedness
is considered by a simple approximation. Furthermore turbulence
measurements in diffusion flames by the laser-two-beam-method
are performed. The validity of additional differential equations
for the kinetic energy of turbulence and a length scale for
systems with chemical reactions and large changes of density is
studied.

DFVLR - Research Work on Supersonic Combustion (Abstract)

Research work on supersonic combustion was carried out
at DFVLR from 1962 to the early seventies. First investi-
gations concerning self-ignition of shock induced hydrogen-
air-flames, were followed by work on the self-ignition of
hydrogen-air diffusion flames at Machnumbers of 1,5 to 2,2,
correlation of reaction-kinetic induction times and measured
ignition times, including influence of pressure, temperature
and effects of air dissociation in the preheater). Another
investigation dealt with suitable methods of extending the
self-ignition range of hydrogen - and hydrocarbon-air flames
to lower temperatures (using catalytic effects and preburning).
Reaction-kinetic work dealt with shock-tube experiments on
thermal self-ignition of hydrogen-air mixtures at low pressures
and low temperatures. Another topic was the stabilization of
hydrogen-air flames by flame-holders (base burning) in super-
sonic flows (Machnumber 1,5 to 2,1) at stagnation temperatures
below the self-ignition range.

Shortly before the cancellation of the supersonic combustion
program, work on the length of supersonic hydrogen-air-
diffusion flames was started concerning the turbulent exchange
properties of these flames; however only measurements in the
high subsonic range could be carried out before work had to
be stopped.

The above investigations have been carried out by F. Suttrop,
Th. Just and F. Schmalz, G. Winterfeld and W. Schröter.

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RESEARCH ON MECHANISMS OF SUPERSONIC COMBUSTION AND

EXTERNAL BURNING RELEVANT TO U. S. NAVY REQUIREMENTS*

R. C. Orth[†], P. J. Waltrup[††], R. T. Cusick[†††], and J. A. Schetz[††††]

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ABSTRACT

The Airbreathing Propulsion Program for NAVSEA being conducted
at the Johns Hopkins University Applied Physics Laboratory Propulsion
Research Laboratory (PRL) includes exploratory development of air inlets,
combustors, fuels and fuel control, nozzles and other engine components as
well as engine simulations, engine tests, and propulsion performance analyses
in relation to potential missions. Components appropriate to liquid-fueled
ramjets for supersonic (Mach 2 to 4) and hypersonic (Mach 5 to 8) missiles
are under development.

Direct-connect tests of cylindrical supersonic combustors with a
rearward facing step increase in cross-sectional area immediately behind the
fuel injection station followed by a downstream divergent conical section
(step-cyl-cone combustor) are being tested at simulated low-altitude, low

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flight Mach number conditions to determine performance with various high
energy metalized hydrocarbon liquid fuel blends and ignition aids such as
spark ignitors, UV photochemical ignitors and piloting techniques. During
the past several years the components were tested at simulated high-altitude,
high-flight Mach number conditions. A computer-operated Supervisory Control
System has been developed to provide the precise and safe control required in
these tests at high air and fuel mass flows and pressures. Details of the
measurement and testing techniques, as well as the computer-operated control
system will be discussed.

The connected-pipe test setup also includes an axisymmetric, con-
toured exit nozzle following the step-cyl-cone combustor. The flow field for
this nozzle has been analyzed using a method-of-characteristics solution.
Theoretical exit profiles have been generated for non-burning and burning
cases with non-uniform nozzle entrance profiles and compared with experimental
results when complete solutions have been obtained. Agreement between theory
and experiment is similar to that using uniform nozzle entrance conditions.

In the program on the use of external burning of the exhausts from
fuel-rich solid propellants to reduce base drag of projectiles (supported by
NAVSEA via the Naval Ordnance Station), APL has prepared to conduct experiments
and has developed analyses to describe the flow in the base region with and
without base and/or external burning. An improved corner-flow and downstream
solution for the case of a planar base with mass injection/combustion has
been described and planar heat addition in the external supersonic flow has
been included. A brief discussion of the test setup and the analytical work
will be presented.

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Review of Experiments Conducted by BRL in
Fumer Technology

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A 1971 BRL Report[1] on unusual projectile shapes concluded that a significant increase in the effectiveness of direct fire ammunition could be achieved by combination of a low-drag ballistic shape and the injection of hot gas into the wake region of the projectile to minimize the base drag. Since 1971 the Ballistic Research Laboratories in conjunction with Frankford Arsenal and the Naval Surface Weapon Center's White Oak Laboratory have been engaged in an experimental program to develop the technology for application of fumers to ammunition design.

The majority of the experimental work consisted of wind tunnel experiments in which candidate fumer compositions were tested in the NSWC White Oak Laboratory's Hypersonic Tunnel. The facility for these experiments has been described previously.[2] Some pertinent points are that free-stream temperature and pressure in the supersonic flow correspond to ambient conditions; the fumer mix was remotely ignited, thereby allowing the supersonic flow to stabilize before the fumer started to burn; and the wind tunnel model could be spun up to 50,000 rpm.

Three separate wind tunnel entries were made during the program. The initial experiments were designed to check the experimental facility with regard to remote ignition and to the ability of the turbine to spin the wind tunnel model. The second set of tests was performed to see if the observed base pressure raise during combustion could be correlated to some feature of the fumer mix, and to see what the limit would be on base drag reduction by direct injection into the near-wake. The experiments were designed to see if the base drag reduction could be correlated to an injection parameter, I, defined as

$$ I = \frac{\dot{m}}{\rho_\infty U_\infty A} , \tag{1} $$

where $\dot{m}$ = mass burning rate,

ρ_∞ = free stream density,

U_∞ = air speed,

A = area at the base of the projectile.

Previous results[3] from the U.K. showed that the base drag reduction could be correlated to such a quantity. These results, however, were obtained in a wind tunnel in which gases with well-controlled values of $\dot{m}$ were injected into the wake region. We wished to see if the mass burning rate of the solid fumer mix could be used for $\dot{m}$ in equation (1) and still get a correlation between C_{Db} and I. Pyrotechnics were chosen for the fumer mixes, since it was well established that such mixtures could ignite and burn in the base of a supersonic projectile during flight. It was also necessary to use a pyrotechnic with a steady burning rate. A mix designated R20C was found to be ideal for this purpose. The results of the second wind tunnel entry clearly demonstrated that the base drag reduction could be correlated to the injection parameter using the pyrotechnic mass burning rate.[4]

The final set of tests was made in order to expand the number of fuels and oxidizers to see if the results obtained using R20C could be generalized. The list below contains the fuels and oxidizers examined:

Fuels	Oxidizers
MgH_2	SrO_2
ZrH_2	$Sr(NO_3)_2$
Zr	$KClO_4$
Ti	NH_4ClO_4
B	BaO_2
$NaBH_4$	$BaCrO_4$

For the pyrotechnic mixes which burned smoothly, it was shown that the results for R20C could be generalized. The base drag coefficient could be related to the injection parameter by

$$C_{Db} = C_{Db_{min}} + (C_{Db_o} - C_{Db_{min}}) \, e^{-JxI} , \qquad (2)$$

where C_{Db} = base drag coefficient during combustion,

$C_{Db_{min}}$ = minimum base drag coefficient achievable through combustion,

C_{Db_o} = base drag coefficient with no combustion,

J = constant.

The U.K. investigators had proposed[3] an equation identical to equation (2) with $C_{Db_{min}} = 0$. Our tests indicated that the base drag coefficient did not go to zero at large values of I, but that an extra term with the $C_{Db_{min}}$ was needed in order to properly fit the experimentally observed C_{Db} vs I.

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Future work is aimed toward applying fumer technology to indirect-fire projectiles, and broadening our scope to include external burning and ramjets as other in-flight propulsion techniques. At present rocket-assist is the sole technique used to increase the range of artillery projectiles by in-flight propulsion. We hope to eventually develop the technology of in-flight propulsion to the point where the projectile designer will have four options at his disposal rather than just rocket-assist. We feel that further increases in the range of artillery will have to come from some form of in-flight propulsion, since the use of higher flame temperature propellants is precluded because of unacceptably low tube life.

1 L. C. MacAllister _et al_, "A Compendium of Ballistic Properties of Projectiles of Possible Interest in Small Arms," BRL Report No. 1532, February 1971.

2 J. R. Ward _et al_, "Wind Tunnel Study of Base Drag Reduction by Combustion of Pyrotechnics," BRL Report No. 1745, October 1974.

3 J. E. Bowman and W. A. Clayden, "Reduction in Base Drag by Gas Ejection," RARDE Report 4/69, December 1969.

4 J. R. Ward _et al_, "Wind Tunnel Experiments on the Effect of Near-Wake Combustion on the Base Drag of Supersonic Projectiles," BRL Memorandum Report No. 2588, February 1976.

BASE REGION COMBUSTION PHENOMENA

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Propulsion in any fluid gives rise to a drag on the body in motion. A part of the drag that arises at the rear of the body, due to a reduction of pressure on the base region of the body, is commonly referred to as the base drag. A striking example of the base drag phenomenon is the drag that arises on a thin plate that moves normal to itself at any speed in any fluid. The flow field that arises at the rear of the plate is of course a function of the Reynolds and Mach numbers. The flow field is also a function of the heat transfer between the plate and the surrounding fluid if there is any heat exchange.

If the same experiment is repeated on a body with a volume and a flat base, one again observes a reduction in pressure on the base. The resulting base drag then becomes a function of the boundary layer characteristics at the base corner; hence, in addition to the other parameters, the base corner geometry becomes of great significance.

There has been considerable technological and fundamental interest in base flow phenomena. The technological interest is in reducing the base drag, in controlling the heat exchange between the body and the fluid, in determining the mixing characteristics between a base region jet and the surrounding fluid and, in general, in controlling the motion of the propelling body.

The fundamental fluid mechanical interest in the phenomena arises on account of the delicate balance of flow forces in the base region and the strong coupling between the flow some distance upstream of the base and the flow far downstream of the body. The problem has essentially remained unsolved in rational fluid mechanics. The motion of a super-sonic projectile with a flat base provides a direct illustration of the coupling between the flow on the body and the far wake through the recirculation, mixing and flow compression processes occurring in the near wake region. A sting attached to the rear of the projectile changes this flow configuration in a detectable fashion.

The methods of controlling the base flow phenomena may be divided broadly into two categories: (1) those involving changes in the geometry of the propelling body in the base region and (2) those in which the flow in the vicinity of the body is affected by the addition of mass or

energy. Some examples of the first category are boat-tailing and
attachments to the body. In the second category, in addition to the
effects of heat exchange mentioned earlier, the base flow can be changed
with the injection of inert or chemically reactive fluids into the base
region. In controlling base flow phenomena with injection, the following
can be varied: the mass of injectant, the location of injection and,
to some extent, the location of chemical action and enthalpy change in
the base region. For convenience, it has become common practice to
distinguish (i) base injection and combustion from (ii) external injection
and combustion, based on whether the injection occurs (i) through the
base or (ii) upstream of the base corner. There are obviously certain
common features between the base and external combustion configurations,
for example the characteristic scales that govern the basic flow coupling.
There are also special features in each case, for example the manner in
which the coupling between the external flow and the flow in the immediate
vicinity of the base is sought to be changed.

We consider an axisymmetric projectile with a flat base in motion
at a supersonic velocity and at a Reynolds number for which the mixing
layer between the recirculation region and the outer flow in the vicinity
of the base is turbulent. If we now consider inert gas injection, what-
ever the location of injection, the principal parameters are the density
of the injected fluid and the mass and velocity of injection. They can
be related to (a) the body boundary layer parameters and (b) the mass
that can be entrained into the mixing layer. Several regimes of operation
can be identified on this basis.

Now, when we consider external injection, the situation becomes
extremely complicated by (a) the flow processes in the vicinity of the
injection slot or hole, (b) the occurrence of a distinct mixing layer
between the injected fluid and the external flow and (c) in the case of
a supersonic projectile, the coupling between the injected fluid and
the base corner expansion-compression processes. There is no satisfactory
method of obtaining solutions to any of the foregoing problems at the
present time. For example, the calculation or measurement of flow in
the vicinity of an injection slot taking account of the upstream effects
and the recirculation zone downstream of the slot is an unsolved problem:
yet, this portion of the flow development has a tremendous effect on the
subsequent development of the mixing.

When the injectant is a chemically reactive fluid, there is no
basic change in the fluid dynamical processes except that the distri-
bution of enthalpy sources has to be taken into account.

In the case of base combustion the problem becomes complicated
because one has to take into account the added energy distribution in
the entire near wake region. Calculations and measurements of velocity,
temperature and concentration in a recirculation region and a neighboring
mixing layer present extremely difficult problems.

In the case of external combustion, there are identical problems
in analysis and experiment. The very fact that combustion may become

confined to a particular region in the external flow requires a fairly precise definition of the heat addition region. Analogical studies may prove misleading.

Both in base and external combustion, one is faced with the problems of (a) determining the optimum fuel, (b) assuring ignition and (c) avoiding instabilities.

The supersonic projectile is probably the relatively simple case. The subsonic and, even more so, the transonic speed propulsion systems offer even greater challenges in analysis and experimentation.

Intermediate level modelling and experiments are central to progress in this area. In external combustion schemes, this may consist in establishing experimentally the boundaries of the external combustion zone and the pressure distribution along the axis and relating those in an integral analysis to the changes in the recirculation zone and the mixing layer.

PROJECTILE BASE FLOW CONTROL WITH COMBUSTION

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The problem under study is the determination of the optimum injection of mass and enthalpy in the base region, the optimum relating to the greatest increase in base pressure with the simplest geometry of the base. The interest in the current project is in small projectiles and therefore there is emphasis on a rather small mass of injection through the base. The projectiles under consideration here are expected to move at supersonic velocities, the Mach number varying from about 2.5 to 1.5 from start to impact.

The wake of a projectile is characterized by several striking features: (a) the separation, expansion, compression processes at the base corner, (b) the formation of the recirculation zone behind the base, with a stagnation point at the axis, (c) the structure and behavior of the shear layer connecting the recirculation zone with the external steam and (d) the formation of a neck in the wake. The entire wake flow is of course dependent only upon the boundary layer development on the body, the Mach number of the external steam relative to the projectile and the base geometry. With a flat base, the base pressure is remarkably uniform while downstream there arises a pressure distribution, in general, both in the streamwise and in the lateral directions.

One of the remarkable features of the recirculation zone is that with small injection the recirculation zone continues to remain "closed" with a stagnation point at the axis. Increased injection tends to elongate the closed recirculation zone, the circulation possibly remaining constant.

In general, the shear layer for the projectiles of interest is turbulent in character; the projectile boundary layer is also turbulent. There is obviously no certainty that the intensity and scale of turbulence along the shear layer remain constant. When there arises chemical reaction in the wake as in the present case, several other uncertainties arise as the turbulence model is made detailed to take account of (a) the concentration and temperature fluctuations and (b) the chemical reaction kinetics.

In view of the foregoing, we have adopted two methods of attack to study base pressure control with injection and combustion: (1) replacing the shear layer with an annular turbulent jet, the origin of the jet becoming adjusted with the injection and (2) connecting the recirculation zone with the external flow through the shear layer using boundary layer type approximations, imposing wake structure conditions related to the reattachment point and the wake neck, and introducing distributed enthalpy sources.

We have compared the results obtained from the first approach (jet analogy) with experimental results obtained in wind tunnel tests where the molecular weight and temperature of the injectant have been varied over certain ranges. This is essentially in the nature of a parametric study involving an injection parameter (equal to, for example, the injectant impulse), the expansion angle of the supersonic flow at the corner and the length of the recirculation zone.

The second method of attack (limited interaction analysis) also utilizes the distribution of mass and enthalpy sources as a parameter. The chemical reactive mixing between the injectant and the surroundings is completely separated out from the wake fluid dynamics. The principal reason for this is that, in the absence of the very detailed information that is required for the analysis of turbulent mixing and enthalpy generation, one would do better by establishing the effect of enthalpy source distribution in the first instance and then relating separately the injectant and its chemistry to the mass and enthalpy distribution functions.

In the limited interaction analysis it is assumed that the injected mass escapes through the shear layer. The mass may be distributed in different ways depending upon the geometry of injection. For example, if the injection is located at the base corner, the injectant enters the shear layer at that location. On the other hand if the injection is distributed at the base, one can adopt an entrainment function along the shear layer. In light of recent advances in turbulent mixing theory, it is assumed that the entrainment of injected mass is a constant per unit length of the shear layer upto the stagnation point on the axis. The generated enthalpy is specified in terms of sources either distributed in the recirculation zone (well-stirred reactor) or distributed in the shear layer (diffusion controlled flame or direct injection of fuel into the shear layer).

The analysis is based upon an iteration of a guessed pressure distribution along the axis. One accepts solutions that satisfy the criterion of a closed recirculation zone and a wake neck. Experimental results are required to provide a guide on the axial pressure distribution and the location of the shear layer for various injection parameters. The analysis is based on an integral approach to flow equations deduced under boundary layer approximations. The development of a computer program for this analysis is nearing completion. One can study then the effects of the geometry of injection and the effects of the distribution of enthalpy.

An important aspect of this model is the possibility of a direct extension of the analysis to external injection and combustion cases.

Work is in progress concerning the application of an integral type analysis to the base flow problem for a projectile in rotation.

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Injection Processes Associated with

External and Base Burning

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The influence of different injector designs on the base pressure
rise through external burning is being studied. For the experiments
a two-dimensional wind-tunnel is being used in which the external
burning environment is simulated. The base pressure rise was
significantly improved over the commonly used injector concept with
supersonic injection into the airstream by two methods which will be
described in the presentation. Color movies of the combustion process
and freestream pressure/temperature measurements provide insight into
the processes which provide   the improvements. The results of this
study are of significant importance for the design of external burning
assisted projectiles.

ABSTRACT

A MODEL OF EXTERNAL BURNING OF LIQUID FUELS*

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A computer model of external burning of liquid fuel (EB) was reported in
Reference 1. This model consisted of two regions. Air entered the inner
region, controlled by jet shock shapes in the penetration and spreading
planes. During downstream flow in the inner region, the drop cloud
evaporated and burned at equilibrium, controlled by the conservation
equations.

The pressure of the inner region was required to be equal to the pressure
at the inner boundary of the outer region. This outer region was assumed
axially symmetric and annular in shape; it was calculated stepwise down-
stream, together with the inner region. The interface between the two
regions was a dividing streamline. This implied that all air that parti-
cipated in combustion entered the inner region through the upstream part
of the jet shock, and that none entered through downstream mixing.

Considerable experience in application of the model to experimental data was
accumulated in succeeding years, and as a result, it became apparent that
performance predictions were systematically lower than experimental data, and
that the probable cause was that too little air was allowed to react with the

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fuel downstream of the injectant. As a result, the model of Reference 1 was modified to include transport of air into the combustion region by turbulent mixing. This inward transport of air is represented by an outward stepping of the dividing streamline, which together with the wall bounds the combustion region, as the computation marches downstream.

In order to control the rate of inward air transport, it was necessary to develop a method of calculating the outward diffusion of the boundaries of the vapor evolved by evaporation from the drop cloud. This was done by considering each liquid drop as a source of vapor, which is evolved under the control of an evaporation rate constant, and which diffuses laterally downstream just as does the injectant from a single gas jet. Integration over all sources, i.e. over all drops, then gives the rate of outward diffusion of vapor.

The present paper describes the resulting model, including the conservation equations, the use of jet penetration and spreading data to calculate the nose region of the jet shock, and the jet breakup and droplet evaporation calculations. The method of controlling the outward stepping of the dividing streamline is given in some detail.

Finally, the good resulting correlation with data of MDAC, GASL, and Boeing (EBBO program), on single surface injectors, will be shown. This correlation is shown in Figures 1-6 of this Abstract, with numerical values of specific impulse removed in order to be unclassified. Good correlation has been achieved for some 37 data points over a range of from 0.2 to 4.3 lb/sec per injector, for pentaborane (Figures 1-4) and TEA. The latter depends on a method of adjusting the evaporation rate constant. Results for TEA are shown in Figure 5. Results of two runs that were observed to fail to ignite indicate that the effects of evaporation alone are also properly accounted for (Figure 6).

Reference
1. D. E. Hill, B. R. Phillips and D. P. Spracklen, "An Analysis to Predict the Specific Impulse Resulting from External Burning (U)," McDonnell Douglas Paper 4779, Presented to the AIAA 4th Propulsion Joint Specialist Conference, Cleveland, Ohio, June 1968 (Confidential Paper).
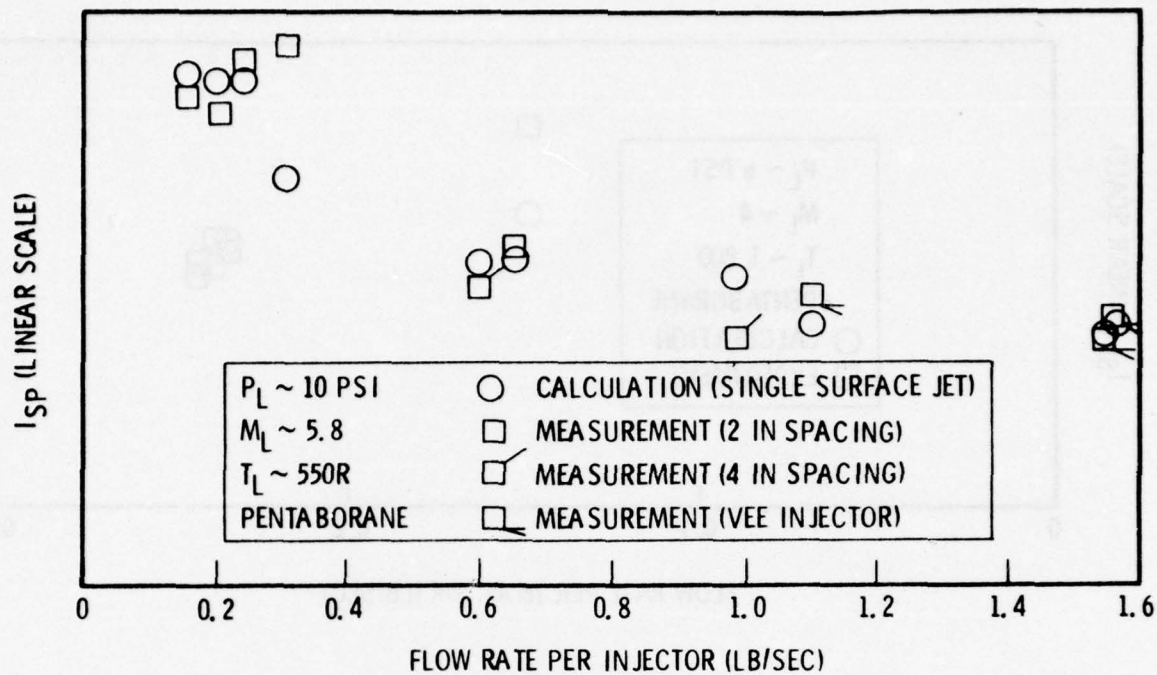
Figure 1. Comparison with Experiment— UpSTAGE Surface Injector Data
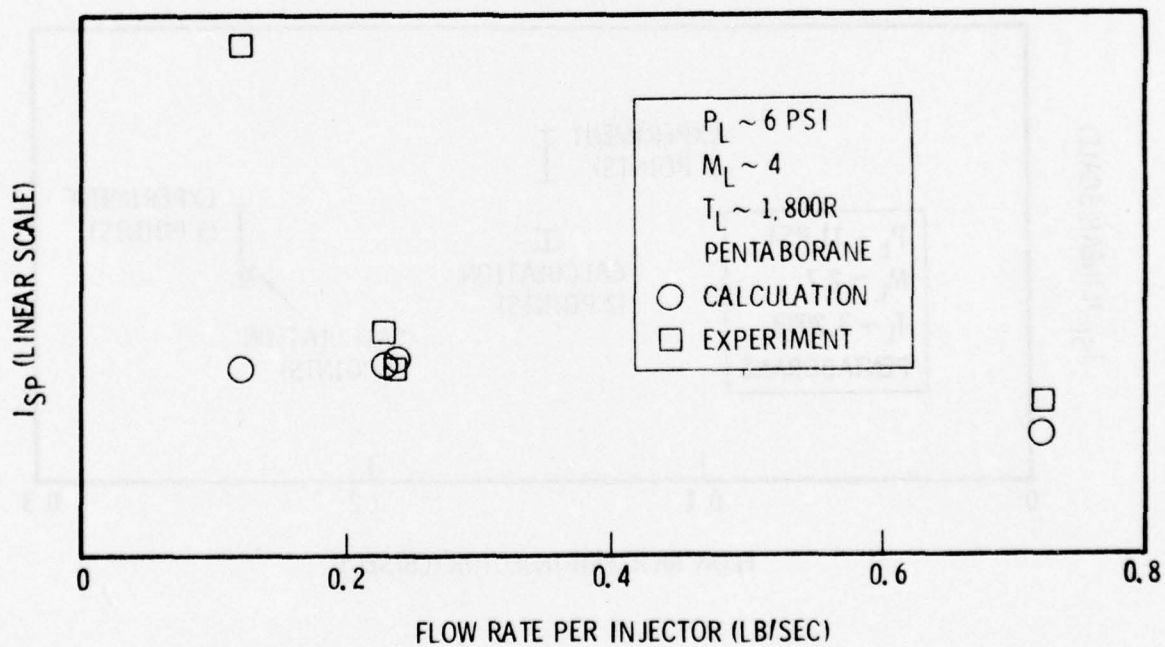
Figure 2. Comparison with Experiment—GASL Single-Injector Data

45
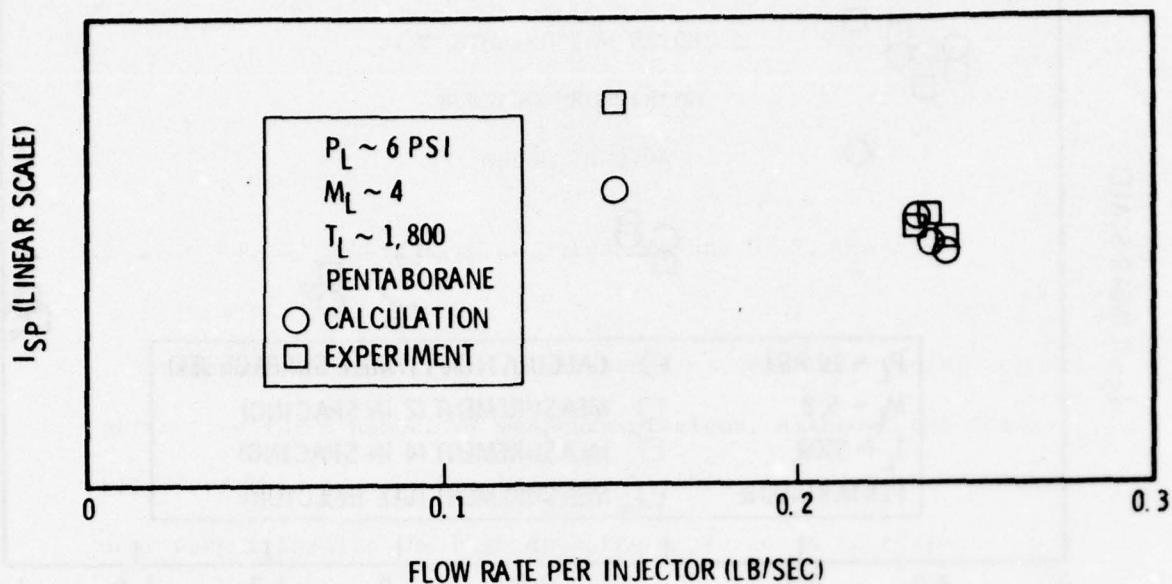
Figure 3. Comparison with Experiment — Multiple-Injector Data
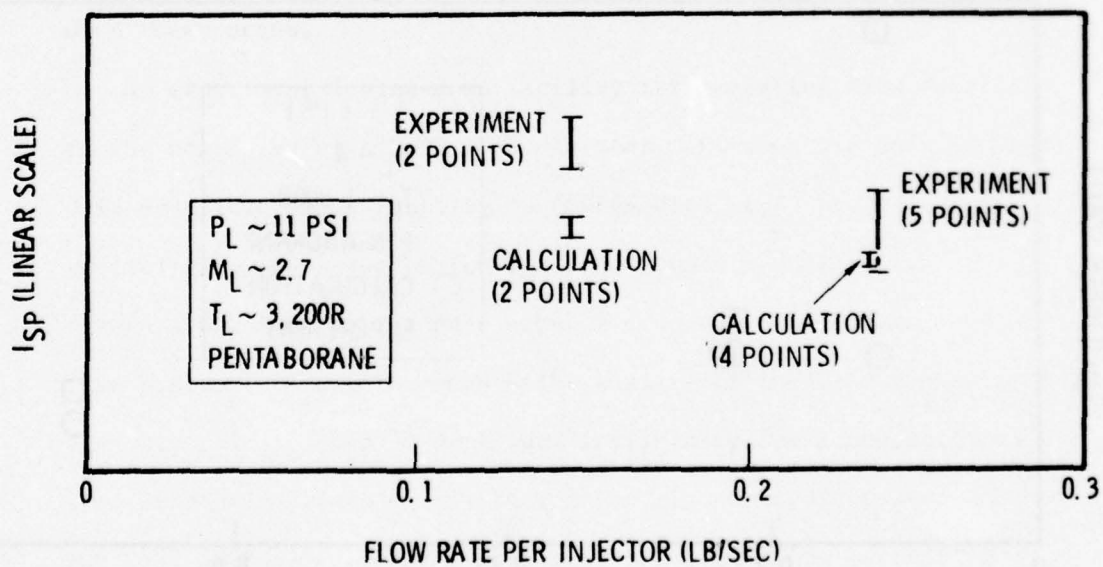
Figure 4. Comparison with Experiment — Multiple-Injector Data

P_L ~ 5 PSI
M_L ~ 5
T_L ~ 440R
TEA INJECTANT
□ EXPERIMENT
● CALCULATION USING k_{PB}
○ CALCULATION USING k_{TEA}
(EQUATION 37)

FLAGGED SYMBOLS CORRESPOND
TO MULTIPLE INJECTOR TESTS
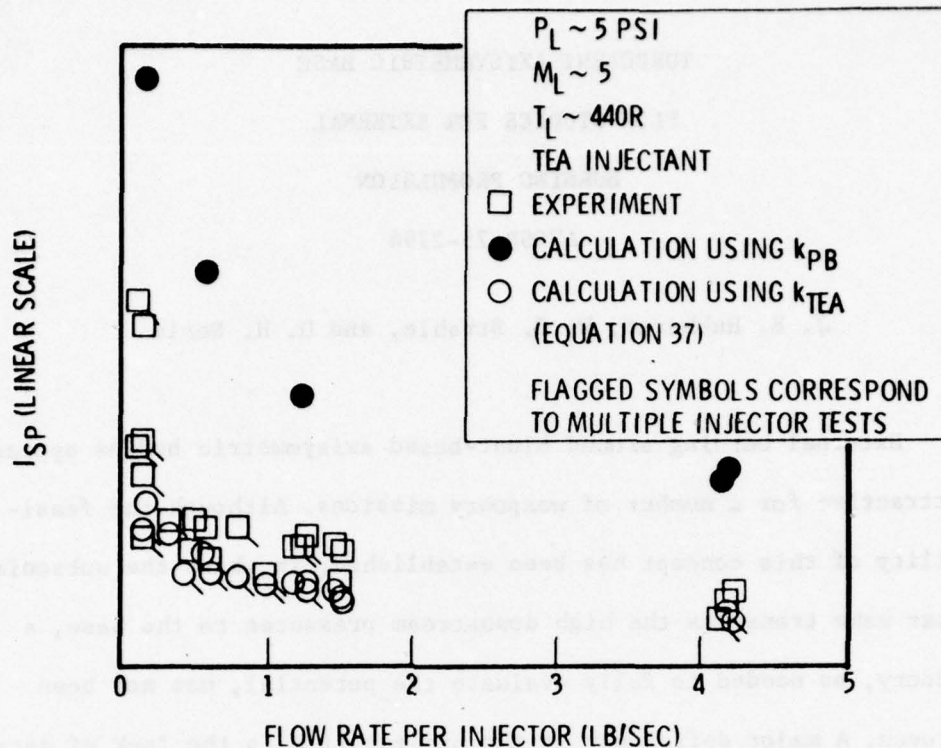
Figure 5. Comparison with Experiment — EBBO Data

$\dot{W}$ = 0.230 TO 0.238 LB/SEC
PENTABORANE INJECTANT

TYPICAL FORM OF
CORRELATION AS
DEVELOPED IN
UpSTAGE PROGRAM

○ CALCULATION (EQUILIBRIUM)
□ EXPERIMENT
(COMBUSTION OBSERVED)
□ EXPERIMENT
(NO COMBUSTION OBSERVED)
● CALCULATION
(INERT DOWNSTREAM)

$P_L M_L^{1.5}/T_L$

7×10^{-2}
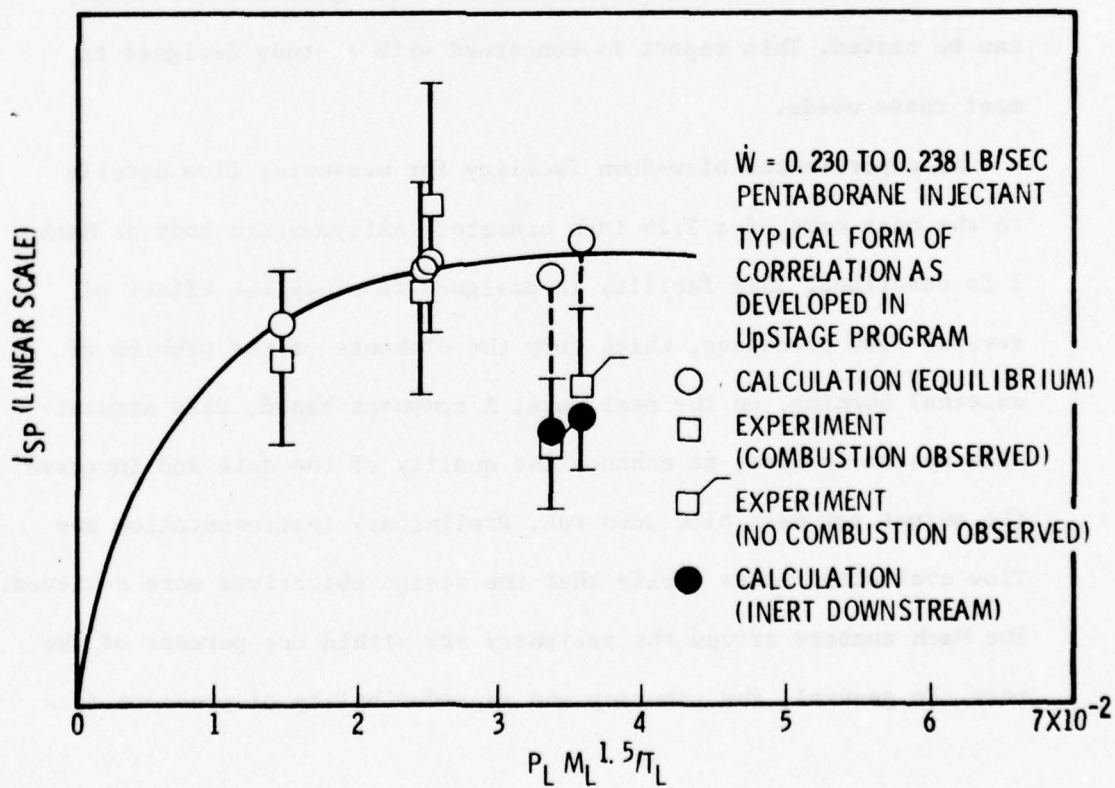
Figure 6. Comparison with Experiment — GASL Single-Injector Data

TURBULENT AXISYMMETRIC BASE

FLOW STUDIES FOR EXTERNAL

BURNING PROPULSION

AFOSR 75-2794

J. E. Hubbartt, W. C. Strahle, and D. H. Neale

External burning around blunt-based axisymmetric bodies appears
attractive for a number of weaponry missions. Although the feasi-
bility of this concept has been established, in which the subsonic
near wake transmits the high downstream pressures to the base, a
theory, as needed to fully evaluate the potential, has not been
proven. A major deficiency at the present time is the lack of data
which reveal the principal flow features and against which theory
can be tested. This report is concerned with a study designed to
meet these needs.

An experimental blow-down facility for measuring flow details
in the near wake of a 2.25 inch diameter, axisymmetric body at Mach
3 is described. This facility is designed to study the effect of
several flow processes, which form the elements of the problem of
external burning, on the near wake. A computer-based, data acquisi-
tion system is used, to enhance the quality of the data and increase
the output for each blow-down run. Preliminary instrumentation and
flow evaluation tests verify that the design objectives were achieved.
The Mach numbers around the periphery are within one percent of the
mean. In general, the accuracy and reproducibility of pressure data

are conservatively within two percent. Deceleration to subsonic
speeds downstream of the base is satisfactorily accomplished in
a constant-area shock diffuser without interacting with the near
wake. In addition, essentially adiabatic flow exists during the
entire blow-down period.

Base pressures measured without base flow disturbances are in
good agreement with available data. In addition, the base pressure
is independent of Reynolds number over the range 2.5×10^6 to 5×10^6
based on the body diameter. This corresponds to an altitude range
of about 20,000 to 40,000 feet for Mach 3 flight of a 5 inch diameter
projectile. Results of wake surveys show that the rear stagnation
point and the centerline sonic point are located three and five radii
downstream of the base plane.

Test results are also reported for wakes disturbed by axisymmet-
ric external compression surfaces designed to simulate the compression
waves emanating from combustion zones external to the near wake. Axisym-
metric compression surfaces are machined into the outer, wind-tunnel
ducting. These compression surfaces can be translated streamwise rel-
ative to the base by installing spacers. Results for two compression
surfaces, designed for the same total heat input but different heat-
ing rates, are presented. These results show that base drag can be
eliminated and, in fact, base thrust can be achieved. The shorter
combustion zone gave the highest base pressure. More importantly,
it is found that axial movement of the compression surfaces over a
relatively large range affects the base pressure only slightly. In
this range, the wake structure length scales are enforced by the

compression surface location; as the compression surface is moved downstream the near wake length increases. With the compression section located downstream of this range, however, the recirculation zone and the base pressure becomes essentially the same as those without external compression while the acceleration downstream of the rear stagnation point is reduced as a result of the externally induced compression. Radial Mach number profiles with and without external compression show that the basic structure of the near wake is not altered under compression. Furthermore, the Mach numbers vary smoothly. In addition, static pressure profiles show that radial variations in the static pressures are relatively small in the shear region.

The next series of tests will use two additional axisymmetric, external compression sections. The first is designed to simulate the same total heat input but at a yet higher heating rate. The second will be selected on the basis of the previous results with external compression. Subsequent tests will concentrate on other near wake disturbances which form the elements of the problem of external burning for propulsion. These will include investigations of (a) the effects of entropy layers adjacent to the near wake created by axisymmetric and discrete probes near the base of the body, (b) the effects of cold air injection peripheral to the base in discrete jets, and (c) the effects of base bleed. A new model of the near wake flow currently under development will be used to analytically investigate the above effects, and correlations of the experiments and theory will be obtained.

PRELIMINARY EVALUATION OF EXTERNAL BURNING PROPULSION

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The external burning propulsion concept offers the potential for performance which is superior to a conventional rocket in many applications. In this propulsion concept, exhaust from a fuel-rich solid propellant is injected transversely through the vehicle boundary layer into the supersonic air stream surrounding the recirculation zone at the vehicle base. Mixing and supersonic combustion occur with the resulting pressure rise being transmitted to the vehicle base through the near wake. Thus, base pressures greater than free stream static are achievable, thereby producing net thrust.

Results of an investigation to confirm the feasibility of the external burning concept are reported. The objective of the investigation was to verify the validity of the concept as well as to determine performance over a range of simulated operating conditions. Eleven external burning propulsion tests were conducted at AEDC using an eight-inch diameter model. Testing was conducted at simulated pressure altitudes of 30,000, 45,000 and 60,000 feet at Mach 2.0 and 45,000 feet at Mach 2.5. A single combination of propellant composition, injection configuration and progressive fuel flow rate schedule was used for all tests. Data acquisition consisted of temporal pressure and temperature measurements on the vehicle, along the test section wall and in the vehicle wake.

Post-test analysis of the data did not provide the conclusive concept verification originally sought. Rather, pressure data associated with the base and wake region displayed an anomalous sudden pressure rise midway through each test. This pressure rise had previously been attributed to such phenomena as injection shock merger, tunnel wall interference or communication with the diffuser. However, a new review of the data correlates this sudden pressure rise with the onset of external burning. The basis for this new hypothesis is discussed in the current paper as are the possibilities of tunnel wall or diffuser interference.

As a result of the new hypothesis, data previously believed to be not valid, are now believed to be feasible. These data indicated a maximum base pressure ratio at the Mach 2.0, 30,000 foot altitude test condition of about 1.35. At 45,000 feet, the highest measured base pressure ratio was approximately 1.75. However, at the 60,000 foot, Mach 2.0 condition, the heat release at the onset of external burning choked the tunnel and invalidated that data.

Test movies and model temperature measurements indicated that the mechanism of base pressure rise was one of external burning as opposed to base burning directly in the recirculation bubble trailing the vehicle base. The lack of significant temperature rises on the model surface also indicated that the heat transfer is not severe with the current injection configuration and propellant.

ANALYTICAL STUDIES OF
EXTERNAL BURNING PROPULSION[1]

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ARO, Incorporated

The concept of external burning propulsion, in which combustion occurs in the supersonic stream adjacent to a missile near wake, has been of considerable interest to several DOD agencies. During FY75, an AFRPL-sponsored test program on this propulsion concept was conducted at the AEDC. Although missile base pressures higher than freestream static pressure were measured during the tests, questions about tunnel interference effects on the base pressure were left unresolved. Therefore, an analytical study was undertaken in FY76 in an attempt to establish whether or not the waves reflected from the tunnel walls did indeed interfere with the near wake region behind the test body.

The basis of the present analysis of external burning propulsion is a recently developed analytical model of the near wake region behind an axisymmetric body. In the near wake model, the inviscid supersonic external stream is computed with the rotational method of characteristics, and the viscous portion of the wake flow is computed with integral techniques. The predicted base pressure is that which will cause the solution to pass through a Crocco-Lees-type singularity, or critical point, in the recompression region. To analyze the external burning propulsion flow field, the "viscous" method of characteristics was incorporated into the external stream portion of the near wake analysis so that the diffusion flame region in the external flow can be computed. The chemistry in the flame zone is assumed to be in equilibrium.

Initial conditions, at the missile base plane, for the modified near wake analysis were computed with the lateral jet injection analysis of Billig, Orth and Lasky. At the base plane, the 18 injectant jets were modeled as an equivalent annular strip around the missile. Attempts to compute the flow downstream of the base plane for a freestream Mach number of 2 revealed an important and unforeseen feature of the flow field: <u>much of the flow in the flame zone is subsonic.</u> The heat release in the lean portions of the flame is so large that the speed of sound becomes larger than the local velocity. Unfortunately, the subsonic pockets in the flame zone preclude the use of the viscous method of characteristics in this region.

Computations with a parabolic diffusion flame analysis indicate that the subsonic flow region extends far downstream of the base. Because the subsonic region transmits disturbances upstream to the base plane, there is little doubt that the tunnel walls, and possibly the tunnel diffuser, did affect the base pressures measured during the AEDC tests. However, the magnitude of the interference effect has not yet been established.

Because the viscous method of characteristics cannot be used in the partially subsonic flame region, a simpler analytical model to describe the heat release was sought. Since both turbulent mixing and heat release act as effective blockage to the supersonic external flow, a displacement zone model was incorporated into the near wake analysis. The blockage area, A_B, was computed, as a function of axial distance from the base plane, by use of a parabolic diffusion flame analysis. Note that $A_B(x)$ is prescribed in the near wake analysis, but the position of the displacement zone in space is not prescribed. Instead, the displacement zone geometry is computed simultaneously with the computation of the supersonic flow on either side of the displacement zone. Preliminary computations with the displacement zone model indicate that the experimental features of the external burning flow field can be satisfactorily predicted. However, the A_B function must be about twice as large as that computed with the parabolic analysis. The large blockage effect observed in the experiments is possibly related to combustion inefficiency in the gas generator, which would cause the heat release in the flame zone to be larger than predicted.

The major conclusion to be drawn from this study is that, because of the large subsonic region in the flame zone, experiments on the external burning propulsion concept must be carefully designed to avoid interference effects on the missile base pressure. In all of the external burning experiments known to the authors, tunnel interference effects may have been significant.

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FLAME EFFICIENCY, STABILIZATION AND PERFORMANCE IN
PREVAPORIZING/PREMIXING COMBUSTORS

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Advanced combustors of radical design appear necessary (Verkamp et al., 1974) to meet aircraft gas turbine air pollution emission targets (EPA, 1973; Blazowski and Henderson, 1974). One of the more promising approaches involves prevaporization and premixing of the liquid fuel/compressor discharge air upstream of the flame stabilization zone (Mellor, 1976). For such turbojet combustors designed using best available analysis on fuel droplet evaporation rates (Wade et al., 1973; Altenkirch and Mellor, 1974) and approach flow velocities requisite to avoiding flame flashback to the fuel injector (Wade et al., 1973) large extrapolations of literature data are required due to the elevated combustor inlet temperatures and pressures currently of interest. Consequently, both incomplete prevaporization (Mellor, 1976; Altenkirch and Mellor, 1974; Roffe and Ferri, 1976) and flashback (Blazowski and Bresowar, 1974; Wampler et al., 1974; Roffe and Ferri, 1975; Roberts et al., 1975; Blazowski and Walsh, 1975) have been encountered for both conventional and catalytic combustors. In turbine afterburners, combustion efficiency losses are evidenced by reaction continuing in the engine wake (Borghi, 1974), and blowoff and poor combustion efficiency are also of concern in advanced ramjet designs (Stull et al., 1974).

The Purdue program, which is currently in its first year, addresses these problems of combustion efficiency, flame stabilization (flashback and blowoff), and prevaporization in air-breathing engines. The flameholder geometry shown in Fig. 1 has been selected for the experiments and represents a compromise between the disc-in-duct configuration, which has been characterized extensively by Tuttle et al. (1976) for EPA, and the dump ramjet burner of Stull et al. (1974).

Liquid fuel (Jet A) is injected into the center of the tube via a simplex pressure atomizing nozzle. The tube provides a region wherein the fuel can be partially prevaporized and premixed before combustion. The disc serves to stabilize the flame by means of a bluff body recirculation zone which is essentially identical to the flame stabilization used in ramjet and turbojet afterburners.

During this first grant period to date the following preliminary experiments have been completed: 1) combustion efficiency measurements for selected variations in inlet parameters; and 2) determination of flashback and blowoff limits at selected equivalence ratios. Later experiments are designed to assist with the ramjet analytical model development by Dr. R. B. Edelman at R & D Associates.

In addition, semi-empirical scaling approaches are under development at Purdue, using a characteristic time model to describe important physical and chemical processes in spray combustion. Three of these characteristic times are applicable to this study; they are 1) the fuel droplet evaporation time (τ_{eb}), 2) a turbulent mixing time ($\tau_{s\ell}$), and 3) the hydrocarbon and carbon monoxide (CO) oxidation time (τ_{hc}), which represent the heterogeneous, fluid mechanic, and chemical processes occurring in steady-flow combustors.

Extending the approach used by Tuttle et al. (1976) for EPA, the Air Force combustion inefficiency $(1-\eta)$ data are plotted against a parameter X which represents ratios of these characteristic times (Fig. 2). The X parameter is given by

$$X = \frac{b \ \tau_{hc}}{\tau_{s\ell}}$$

where $\quad\quad b = \left(1 - \frac{\tau_F}{\tau_{eb}}\right)^{3/2}$ $\quad\quad$ Tuttle (1976)

$$\tau_F = \frac{A}{V_f}$$

$$\tau_{s\ell} = \frac{D-d}{V_o}$$

and b = amount of fuel penetrating to outer flow

τ_{hc} = oxidation time = a constant for constant inlet temperature

τ_F = time it takes fuel to reach outer flow

$\tau_{s\ell}$ = turbulent mixing time

τ_{eb} = droplet evaporation time calculated from "d^2" law

A = constant empirically determined = 9.14 cm

V_f = velocity of fuel at nozzle

$D-d$ = disc diameter - tube diameter

V_o = inlet air velocity

The measurements, representing data for two different fuel nozzles and four different equivalence ratios, generally fall closely about the linear least-squares-fit relation, with an excellent correlation coefficient of 0.972. The droplet evaporation time, which determines the amount of fuel penetrating to the outer flow, is an important parameter in these results indicating that this configuration is far from totally prevaporized or premixed. These preliminary results show the quantitative relation between combustion inefficiency increases and increasing velocity, droplet size, and equivalence ratio; the effect of inlet temperature and geometry has not yet been completely determined to our satisfaction.

      Blowoff results also show the effect of droplets on the lean limit, and data correlations are being attempted using a similar characteristic time approach. The second flame stabilization limit known as flashback was not a problem with this geometry. In fact, it was not possible to create a flashback situation in the combustor under a wide range of operating conditions. Literature currently becoming available serves to verify that only combustors with flow separation (steps, diverging sections, etc.) experience flashback (Roffe and Ferri, 1976; Craig, 1976), except for catalytic systems with low approach velocities.

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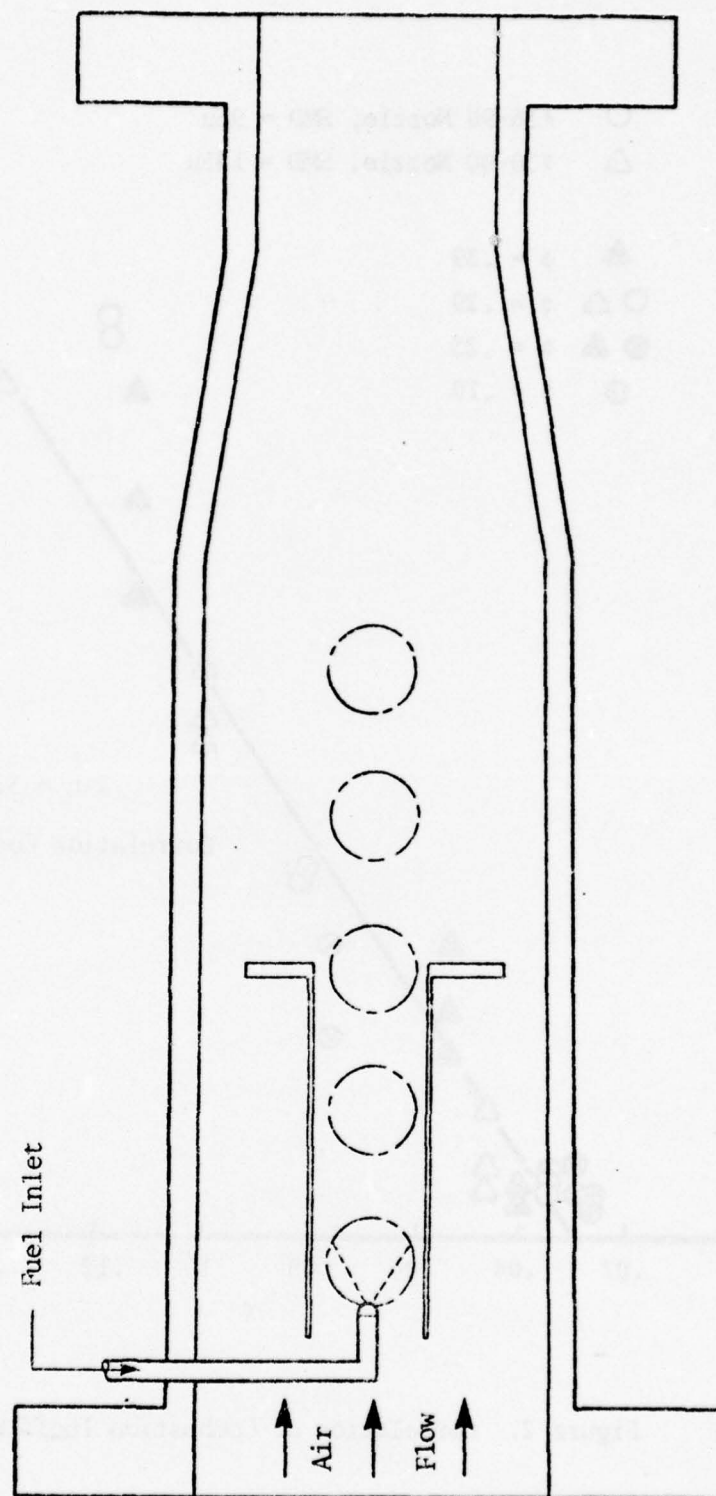
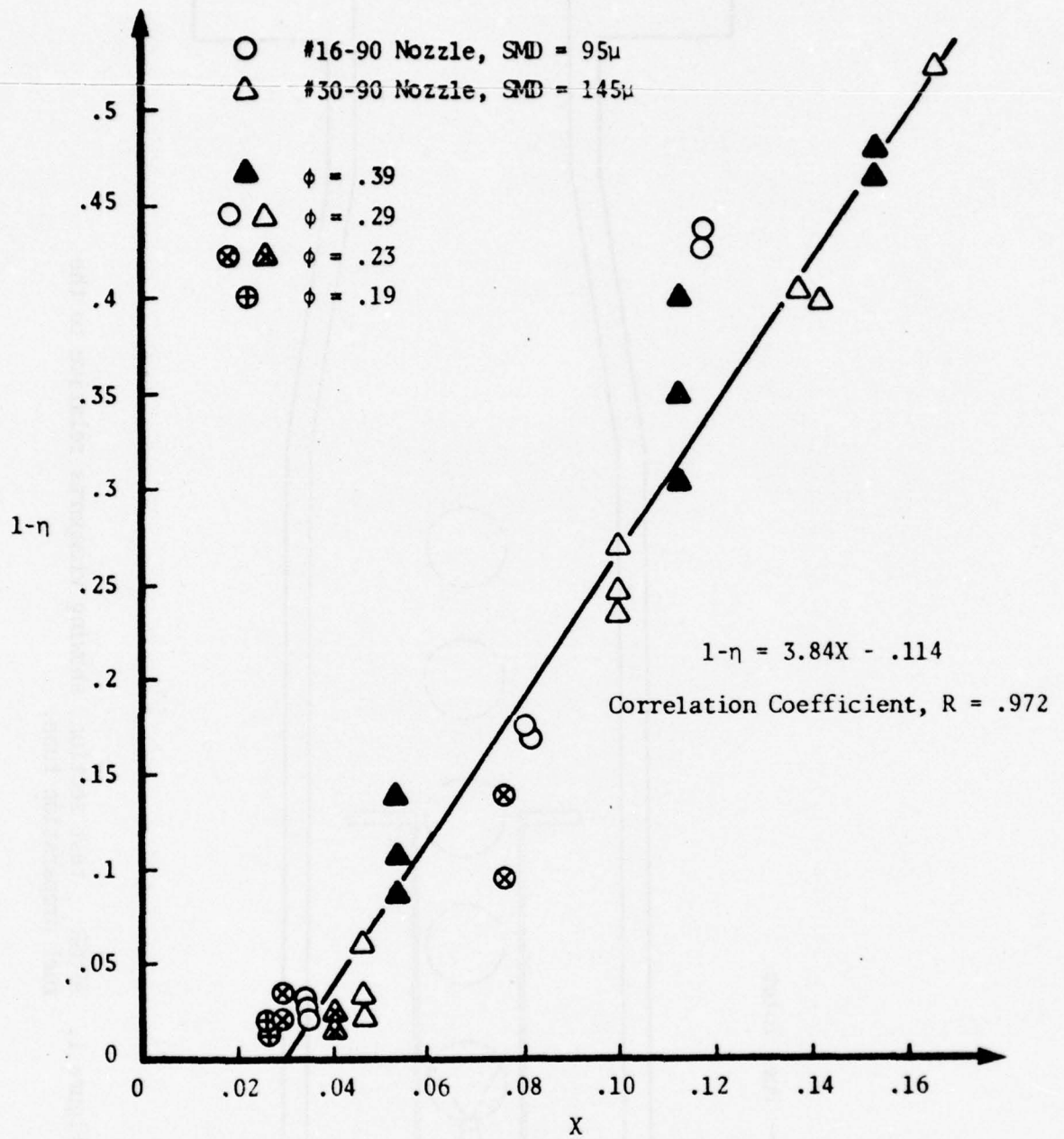Figure 1. AFOSR test section, showing viewports relative to the fuel preparation tube.

Figure 2. Correlation of Combustion Inefficiency

STRATOSPHERIC CRUISE EMISSION REDUCTION PROGRAM

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ABSTRACT

In response to the need for substantial cruise NO_x emission reductions, NASA has initiated the Stratospheric Cruise Emission Reduction Program (SCERP). The SCERP objective is to develop and demonstrate the technology necessary to reduce cruise NO_x emissions by a factor of 6 or more from current levels, in addition to meeting the current Environmental Protection Agency 1979 emission standards for the airport vicinity. The activity will be targeted for the high bypass ratio, high pressure ratio jet engines currently powering the wide-body subsonic transports. Technology evolved by SCERP, although not directly applicable, could aid in the development of low NO_x combustors for future supersonic aircraft engines.

The premixed-prevaporized technique for emission reduction will be explored in the SCERP activity. The results from other studies indicate that this technique has the potential to meet or exceed the program goal. While this technique does not offer the emission reduction potential of the catalytic approach, the practical problems associated with its application are viewed as less severe. However, in considering off-design conditions it is apparent that a form of variable geometry will be necessary to maintain acceptable combustor performance as well as low emissions over the entire flight envelope. In addition, it is expected that an advanced digital control system will be required for the eventual engine application.

The program outline for SCERP is broken into four successive phases leading to an engine demonstration. The initial phase will consist of a number of fundamental studies to establish design criteria for premixed-prevaporized combustors eventually leading to the development and assessment of a number of combustor concepts. In the next phase, a number of variations of each concept will be experimentally screened to

identify the most promising. These designs will then be further developed in Phase III to optimize off-design performance, ignition, liner cooling, altitude relight, etc. The best design will be selected for full-scale engine demonstration in Phase IV.

The Phase I activities will be most critical to program success. A number of fundamental studies are being initiated to examine four key problem areas associated with the practical application of the premixing-prevaporizing concept. These areas are identified as I - Lean Combustion Studies, II - Fuel-Air Preparation, III - Autoignition and Flashback, and IV - Cycle and Performance Constraints.

Several of the lean combustion study elements are extensions of flame-tube investigations underway at NASA. A study of the effect of fuel preparation on emissions will be conducted to examine the influence of the degree of vaporization, mean dropsize, and other spray characteristics. The need for a more thorough understanding of the effects of fuel preparation on emissions has been indicated in the results of two recent NASA sponsored programs. In these studies the expected dependency on the square root of pressure on NO_x emissions is not observed and emission minima occur at intermediate pressures. It has been assumed that this effect is associated with the prevaporization-premixing process and may result from an improvement in vaporization rate at the higher pressure conditions.

Another lean combustion experimental study will parametrically examine the effects of engine cycle parameters on emissions. Emissions measurements of a premixed propane combustor will be made over a wide range of conditions up to 30 atmospheres and 1000 K. The effect of simple flameholder geometries on emissions and combustor performance will be investigated in a third study, while a fourth activity will examine several schemes for lean stability augmentation.

In the area of fuel preparation, engine measurements are being made to characterize the compressor discharge turbulence. The nature of the turbulence in the diffuser inlet may promote fuel mixing and vaporization is fuel is introduced in this region. In addition, techniques for vaporizing fuel external to the combustor will be studied and schemes for controlling radial fuel-air distribution will be examined.

Autoignition and flashback present serious hazards to potential premixing-prevaporizing combustor systems. Many flame-tube studies have experienced autoignition or flashback at

some conditions. It is apparent that at higher cycle pressure ratios if the fuel is given sufficient time to completely vaporize, it may autoignite. The SCERP studies in this area will begin with a parametric study of the factors influencing autoignition delay up to pressures in excess of 25 atm. The effect of hot surfaces on autoignition will also be studied. The effects of boundary layers and engine transients on flashback will be investigated.

The fourth area, identified as engine constraints refers to problems arising from the interfaces between the combustor and the engine. The characteristics of the compressor discharge airflow are of particular concern in a premixing combustor to assure homogeneity of the fuel-air mixture. In addition to the turbulence measurements mentioned previously, an investigation of the circumferential airflow uniformity at the compressor exit will be conducted. Another study will examine the effects of nonideal turbine inlet temperature profiles on turbine life and performance. With an extremely lean primary zone, considerably less dilution air may be available for tailoring the combustor exit temperature profile. As part of a third effort, a simplified combustor model will be incorporated into an engine transient performance computer routine to investigate the interaction of the combustor with the remainder of the engine during acceleration and deceleration. If variable geometry is required, transient performance will be a serious concern.

As the results of the Phase I studies become available, the design data will be applied to combustor concepts. Variable geometry techniques and controls will be incorporated into the designs as required. As the designs evolve, an assessment of their potential with regard to both emissions reduction and practical application will be made. The most promising concepts will then be selected for experimental screening.

An important consideration at the end of the first phase concerns the potential of the various designs for application in existing engines. If a determination is made that the concepts can be adapted to an existing engine with reasonable modifications, then a target engine will be selected and the remaining phases of the program will be directed toward demonstration of the concept in that engine. If, however, a conclusion is reached that the concepts cannot be adapted to an existing engine, then the subsequent program will require a different path. In this approach the concepts will be screened and developed to optimize emissions performance and the best combustors will be used to define the characteristics of a compatible engine.

ABSTRACT

AFAPL TURBOPROPULSION COMBUSTOR PROGRAM OVERVIEW

by Lt Robert M. McGregor

The mission of the Turbine Engine Division of the AF Aero-Propulsion Laboratory is to advance the state-of-the-art of turbopropulsion combustion technology through a systematic and coordinated exploratory research and development program. To effectively pursue this job, we must accurately forecast future turbine engine requirements. In the Components Branch of the Turbine Engine Division, these forecasts are used to establish required performance levels and operating conditions of the next generation of turbine engine components.

The Aero-Propulsion Laboratory sees promise in many new combustor concepts. Three programs presently under contract by AFAPL are the "High Mach Turbopropulsion Combustor"(HMTC), "Augmentor Combustion Stability," and the "Shingle-Liner Combustor."

High Mach Turbopropulsion Combustion

The HMTC addresses a future need for a high through-flow engine. The major advantage of this engine is high thrust in a compact size. The high through-flow concept requires a significant increase in compressor exit Mach number. While there are two ways to address the problem of high compressor exit Mach numbers (high velocity combustion and advanced diffusion), AFAPL has chosen to concentrate on development of an advanced diffuser.

At increased inlet Mach numbers, the pressure loss from conventional diffusers increases significantly, penalizing gas turbine

engine performance and reducing the potential payoff from "high flow" engine technology. The Vortex-Controlled Diffuser (VCD) was selected for evaluation at high diffuser inlet Mach numbers on the basis of its potential low pressure loss, short length, simple construction, and relatively low cost.

VCD parametric performance tests were accomplished prior to final diffuser-combustor flow path design. Tests were performed over a range of inlet Mach numbers to map VCD performance as a function of principal performance parameters -- area ratio, length, VCD bleed rate, and flow distortion. In these tests, a conventional pre-diffuser was employed directly upstream of the VCD to generate flow distortions typical of projected engine applications. The VCD area ratios tested ranged from 1.5 to 3.0; bleed rate ranged from zero to 12%. Results show that VCD diffuser effectiveness increases with length and bleed rate, and decreases with increased area ratio and inlet flow distortion.

Furthermore, a modest amount of VCD bleed increased diffuser static pressure rise dramatically, while reducing diffuser pressure loss approximately 45% (relative to conventional diffusers). With the VCD pressure loss/length performance demonstrated in cold flow testing, mission studies indicate a large payoff from "high flow" technology. The diffuser/combustor system will next be hot tested in Task II of the program currently in progress.

Combustion Stability

Combustion research in the Turbine Engine Division is not limited solely to combustion in the engine core. With the advent of augmented

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mixed-flow turbofan engines, augmentor rumble (low-frequency combustion instability) has become an important and expensive development obstacle. Unfortunately, the suppression of low-frequency oscillations cannot be accomplished using conventional high-frequency "screech" type liners. In addition, longitudinal pressure oscillations which characterize "rumble" can have a detrimental effect on turbofan engine performance--the pressure pulses can propagate directly to the fan through the bypass duct causing reduced surge margin, fan stall, or possibly a serious fan/augmentor coupling. This coupling has the potential of increasing pressure oscillation amplitudes to catastrophic levels.

The Air Force Aero-Propulsion Laboratory currently has three contracted efforts underway to investigate this rumble phenomenon and to develop analytical techniques which can be used as tools to develop rumble-free augmentors. Pratt and Whitney Aircraft group, Government Products Division, is developing this combustion stability prediction model for turbofan afterburners as units. They also share a dual-award contract with Northern Research and Engineering Corporation to develop models which describe the effect of the flame-holder (and heat release at the flameholder) on the stability of combustion in the afterburner. These contracts are set up in such a way that a better understanding of the mechanisms of rumble will result, as well as the acquisition of the analytical design tools.

Shingle Liner

While performance (HMTC) and engine stability are in the forefront of engine development, neither can be separated from the attendant need for durability and low cost. The Shingle Liner Combustor addresses both durability and low cost.

The shingle liner design concept is an advanced combustor cooling technique featuring a new innovation wherein the thermal and mechanical stress loads of the combustor are separated and controlled by independent means. The combustor utilizes a 360° support structure protected by individual segments made from a high temperature alloy.

The outer shell serves as the structural or load-carrying portion of the combustion system while providing impingement cooling for the independent inner segments or shingles. As a result, the shingles provide an effective thermal barrier, protecting the high stress outer shell. The shingle liner is particularly well suited to high temperature rise combustors where cooling airflow is at a premium. Additionally, the shingle concept offers improved liner life due to its thermally relieved mechanical design and its improved maintainability.

The Shingle Liner development was initially sponsored by the Navy and conducted by the General Electric Company. Durability and structural integrity testing is now being conducted under a joint Navy/USAF contract, also with GE. This advanced design concept is currently being considered for both near-term and future propulsion system application.

Research Needs

Like other research and development groups, we in the Components
Branch often find more questions arising from a given project than
answers. For example, with the Vortex Controlled Diffuser, what
disturbances will occur when oil line struts are inserted into the
airflow? Also, will splitters upset the flow if moved closer to
the diffuser? These are two of our future research needs. Others
would include the effect on combustor walls of additional thermal
radiation caused by the use of coal or shale fuels. An off-
shoot of the Shingle Liner may be ceramic shingles with no cooling.
Is this possible with materials now, or do we need new ceramics
and/or cooling schemes? One area which is of considerable value
both in money and time is the development of purely theoretical
modeling programs. Many models are empirical or semi-empirical
and are thus limited in their use. Theoretical models would have universal
applicability, avoiding repetitive hardware builds, and speeding project
completion.

As can be seen by these few but varied needs, there must be
a close, interactive relationship between the research and exploratory
development communities. Without this relationship, turbopropulsion
combustion technology will make no new advances.

Fundamental Modelling of Kinetics, Mixing and Evaporation in Combustors.

J. Swithenbank

Abstract

Chemical energy in the form of liquid hydrocarbon fuel is used in the majority of propulsion systems employed by the USAF. The design of these systems generally calls for very high efficiency over a remarkably wide range of operating conditions. In spite of considerable effort by scientists and engineers throughout the world, there is still no satisfactory design method available which is based on fundamental considerations rather than empirical factors. This is due to the complexity of the system, which involves interaction between droplet evaporation, turbulent mixing and chemical kinetics.

In our analytical approach, a series of interconnecting partially stirred chemical reactors is used to represent the combustion flow field, and entrainment and turbulence theory are linked to evaporation and chemical kinetics. In the previous period, the theory was developed to the point where combustor stability loops could be predicted, but the use of a global kinetic rate model precluded the accurate prediction of efficiency and pollutants. In the present period, the model has been considerably refined to include the simultaneous presence of liquid, air, mixture and products in the reactor. A chemical kinetic scheme involving seventeen reactions has replaced the global kinetics and a very flexible modular computer program has been developed to carry out the calculations. Additional theoretical work has been completed on the laser diffraction droplet sizing technique so that the program now works with the maximum speed in minimum core size. This has required that the program be written in machine language, and has resulted in the time to analyse the size distribution of a spray being reduced from a few minutes to a few seconds. The data aquisition of the spray/particle analyser has also been modified so that 128 sets of data for later analysis can be aquired in periods down to 4 millisecs per set. It is felt that this will aid the

determination of the hitherto unknown dynamic performance of atomizers.

Two experimental rigs have been used to verify the model. A three inch diameter gas turbine combustor has been used extensively in previous work and the crucial effect of fuel preparation on combustor performance has been demonstrated.

As a result of these studies it is felt that fuel preparation is the key to maximizing performance whilst minimizing pollutant formation. Experimental evidence both here and elsewhere shows that premixed, prevapourized fuel can give minimum pollutants, however difficulties are encountered with the off design operation of such fuel preparation systems using liquid fuel, due to flash-back, fuel decomposition etc. On the basis of our analysis, we consider that a solution to this problem is to use a spray whose evaporation time is much shorter than the mixing time. In this case the fuel will burn as a gas even though it is injected as a liquid. To this end, work is now proposed on the use of ultrasonic and other atomizers in the 3 inch combustor since these produce a droplet size of 10 to 20 microns and therefore satisfy the criterion.

The second experimental rig is a novel two stage combustor aimed at minimizing pollutant formation by accurate control of the recirculation, evaporation and residence time distribution. Since the reactor network arrangement is well defined in this combustor, it can easily be related to the theoretical model and comparative tests are now being carried out.

Publications

1. "A Laser Diagnostic Technique for the Measurement of Droplet and Particle Size Distribution". J. Swithenbank, J.M. Beer, D.S. Taylor, D.Abbott, G.C. McCreath, AIAA Paper 76-69. To be published in AIAA Journal.

2. "Concentric Multi-Annular Swirl Burner: Stability limits and Emission Characteristics",A.K.Gupta,J.M. Beér & J.Swithenbank Paper presented at the Fifteenth International Symposium on Combustion, M.I.T., Aug.1976.

MECHANISMS OF EXHAUST POLLUTANT AND PLUME FORMATION
IN CONTINUOUS COMBUSTION
(NA74-012-N)

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INTRODUCTION

The UCI investigation of exhaust pollutant and plume formation
in continuous combustion is a combined analytical and experimental
study of turbulent, backmixed combustion. Predicted profiles of the
flow properties are being systematically compared to experimentally
determined profiles. Model development and evaluation, and studies
of the mechanisms of pollutant and plume formation are currently
being conducted for premixed methane/air and propane/air reactants.

APPROACH

The objectives of the UCI program are directed to clarifying the
relative influence of those mechanisms responsible for pollutant
production in continuous combustion. The investigation is divided
into the following elements:

o Model Development and Evaluation

Evaluation and development of numerical procedures and
models of turbulence by comparing numerically predicted
profiles of velocity, turbulence energy, temperature,
and tracer concentration to experimentally determined
profiles (nonreacting and reacting flow).

Evaluation and development of numerical procedures
and the coupled models of turbulence and chemical
kinetics by comparing numerically predicted profiles
of hydrocarbons, nitric oxides, carbon monoxide,
oxygen, and carbon dioxide mass fraction, and
temperature to experimentally determined profiles
(reacting flow).

o Mechanisms of Pollutant/Plume Formation

Perform parametric studies (theoretical and experi-
mental) to identify the relative contribution of

the chemical reactions, and transport processes
(heat and mass diffusion, fluid mechanics, and
recirculation behavior), and system parameters
(e.g. geometry, flow rates) to pollutant formation.

o Supplemental Studies

   Conduct supplemental studies in support of the
   objectives of the study. In particular, air
   preheat, lean stabilized combustion, nonpre-
   mixed, combustion, and chemical transformations
   in sample probes and sample lines are currently
   under study.

An opposed-reacting-jet combustor (OJC) is adapted for the present
study because of the similarity to practical continuous combustion
devices and the experimental versatility of the OJC. The OJC utilized
a high velocity jet stream opposing the main flow as an aerodynamic
flame holder. The option of a non-premixed system is currently in
design.

The numerical procedures used to solve the governing equations for
the OJC flowfield are based on extended versions of the Imperial College
PISTEP method and a second generation, 3-dimensional program dubbed
TEACH. In cooperation with the Environmental Protection Agency (EPA),
the CRISTY method is operational in the OJC configuration as well.

RESEARCH STATUS

The current reporting period included (1) the test of the numerical
methods against experiment for the case of isothermal flow, (2) expansion
of the experimental facility to include air preheat capability, (3)
initiation of the generation of a broad, experimental data base for the
cases of isothermal and hot flow, and (4) initiation of an in-depth
exploration of chemical transformation that may occur in probes and
lines used to sample and transport nitrogen oxides.

Model Development and Evaluation

Isothermal Flow (nonreacting). The isothermal evaluation of the
PISTEP II and TEACH numerical codes has addressed the effective viscosity
and mass transport submodels. Although favorable qualitative correlation
has been established, deficiencies in the eddy viscosity submodels and
associated boundary conditions used as a foundation for the transport
mechanisms have been identified.

The flowfield hydrodynamics are more accurately represented by the
two-equation submodel because of the intrinsic variable viscosity and
length scale. Comparable solutions may be obtained at considerably less
expense by employing the algebraic submodel.

The mass transport predictions of the algebraic submodel demonstrate
acceptable correlation. The prediction of radial mass transport by the
two-equation submodel in general does not conform to experiment. The
performance of the two-equation submodel may be improved by careful
specification of boundary conditions. In particular, the near wall

-2-

turbulence energy dissipation rate was shown to significantly influence the mixing characteristics of the two-equation submodel.

The results of the isothermal flow studies indicate that the algebraic turbulence submodel performs adequately in describing general fluid flow patterns and mass transport for the conditions investigated. A major impact of the present study is that considerable testing of the numerical model is required for isothermal flow before proceeding to the complicating conditions of combustion. The testing requires a coupled numerical/experimental study and is likely governed by the geometry, inlet and solid boundary conditions of the system under investigation. The hot flow calculations presented here accentuate the inadequate transport characteristics identified in the isothermal flow analysis. Attempts to refine the chemistry submodel or to quantify the interaction of fluid motions on chemical reaction rates are dependent on the correct turbulence model formulation.

Heated Flow (nonreacting). The heated flow evaluation has been initiated by the design and installation of preheat capability. The evaluation will conclude during the continuation year.

Hot Flow (reacting). Hot flow solutions have been obtained with TEACH. Initial experimental data have been obtained in preparation of the coupled numerical/experimental evaluation in the continuation year.

Mechanisms of Pollutant/Plume Formation

The experimental facility is undergoing final modification (inclusion of preheat capability) prior to initiating the scheduled exploration of the mechanisms responsible for pollutant and plume formation in continuous combustion. To improve the signal aquisition of the LDV System, the addition of a counter mode to complement the existing frequency tracking mode is under investigation. The sampling performance of the combustion test facility is being improved as a result of the supplemental, NO probe studies.

Supplementary Studies

The NO probe study has shown significant reduction of nitrogen dioxide (NO_2) to nitric oxide (NO) can occur in sample probes and sample lines, especially in the presence of carbon monoxide (CO) at modest temperatures in stainless steel. The effects of probe history and reducing species in addition to CO will be evaluated in the continuation year.

FUNDAMENTAL COMBUSTION STUDIES
RELATED TO AIR-BREATHING PROPULSION

by

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Research will be described on ignition, combustion and extinction of carbonaceous particles and on structures and propagation speeds of premixed turbulent flames. These studies ultimately are relevant to combustion efficiencies of combustors and smoke emissions therefrom.

Previously experiments had been performed on the combustion of laser-ignited particles of electrode carbon in oxygen-nitrogen mixtures. It was established that these particles self-extinguish before burning to completion, the residue remaining after extinguishment being a highly porous flake-like particle of carbon. A theory for the extinguishment was developed, from which overall kinetic data were derived that agreed with results published by Park and Appleton, based on shock-tube oxidation measurements of carbon blocks. It was deemed desirable to investigate combustion of carbonaceous particles containing materials other than pure carbon, to ascertain whether similar extinction phenomena are observable more generally. As a material having a chemical composition representative of that of particles often found in combustion chambers, Pittsburgh Seam Bituminous coal ($CH_{0.82} O_{0.08} N_{0.015} S_{0.009}$, plus 7.3% ash and 1% moisture) was selected for testing.

Experiments revealed a two-stage combustion process for these laser-ignited, carbonaceous particles, burning in air at atmospheric pressure and having initial characteristic dimensions from 50 to 400μ. The first stage involves a gas-phase burning mechanism, resembling that of a hydrocarbon droplet with the exception that the flame zone often is somewhat asymmetric. The second stage involves a surface burning mechanism occurring on a very small, hot, carbonaceous residue. The first stage is the shorter, typically lasting on the order of one millisecond. The duration of the second stage typically was on the order of a few milliseconds. The types of extinguished residues that occurred with pure carbon were not found with the coal. In fact, the carbon required oxygen enrichment of the atmosphere for combustion to occur, while the coal ignited easily in air. These differences suggest that even the surface-burning mechanism of the coal particles differs significantly from that of carbon, there being enhancement of combustion by either hydrogen content or impurities. An implication of the results is that soot burnup in combustion chambers may occur more readily than theory based on carbon kinetics would predict.

A secondary observation concerned ignition of the carbonaceous particles by the laser. There appears to be a tendency for the particles to break up, emitting many fine particles during the ignition event. This tendency is less pronounced than that observed previously for amorphous boron. It probably is

attributable to the highly irregular and porous structures of pulverized coal particles and to the tendency for very fine fractions to agglomerate within the larger particles tested. Laser radiation is absorbed to some extent within pores, and consequent internal evolution of gas causes fragmentation.

In previous work, structure and propagation speeds of low-intensity, premixed turbulent flames were calculated by a method involving an expansion in a parameter involving the ratio of the RMS turbulent velocity fluctuation to the laminar flame speed. The results turned out to be restricted to flames of very low intensity, thereby imparting highly limited practical interest to the results. A method has been discovered for applying very nearly the same theoretical methodology to the description of flames for arbitrary turbulence intensity in large-scale turbulence. The expansion parameter now becomes the ratio of the laminar flame thickness to a characteristic turbulence scale. The theoretical work, still in progress, potentially affords the opportunity of calculating structures and flame speeds for many premixed turbulent flames of practical interest.

The results of the turbulent-flame calculations predict that turbulence thickens the flame. To calculate the effect of turbulence on the flame speed necessitates going to second order and leads to a very involved analysis. The results show that, if there are velocity fluctuations but no concentration fluctuations in the approach flow, then ignoring an effect of strain-convection interaction, the flame speed increases by an amount proportional to the mean square of the gradient of the time integral of the upstream velocity fluctuation. The Taylor microscale of the turbulence enters naturally into the analysis. The predicted results appear to be in qualitative agreement with results of experiments performed for large turbulence scales and high intensities. It should be emphasized that the theory, being based on a rational expansion technique, contains none of the conventional modeling assumptions and as such comprises entirely a priori predictions.

<u>1976 AFOSR CONTRACTORS MEETING</u>
<u>ON AIR BREATHING COMBUSTION DYNAMICS</u>

Combustion Modeling of Phenomena in
Air Breathing Combustion Engines

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The object of the present work is the further development of a three-dimensional Navier-Stokes calculation procedure for the prediction of combustor flow fields. This work has been jointly sponsored by the AFAPL and the FAA. A companion two-dimensional or axially symmetric Navier-Stokes combustor pollutant prediction procedure has been under development at UTRC for several years initially under FAA, Air Force and EPA sponsorship and more recently under EPA sponsorship alone. Both of these programs are based upon direct numerical solution of the coupled system of nonlinear partial differential conservation equations.

The three-dimensional computational procedure is being developed to predict the coupled flow and chemistry within rectangular or axisymmetric combustors with a discrete circumferential distribution of injection ports. The compressible time-averaged Navier-Stokes equations are solved with coupled pseudo-kinetic equilibrium hydrocarbon chemistry including the effects of turbulence, droplet vaporization and burning, and radiation transport. A two-equation kinetic energy-dissipation turbulence transport model is employed in conjunction with a modified wall function formulation incorporated to circumvent the large computer run times associated with wall boundary layer sublayer resolution.

The governing equations are solved using the Multidimensional Implicit Nonlinear Time-dependent (MINT) procedure developed by Briley and McDonald, which employs a unique linearization technique and a Douglas-Gunn alternating-direction-implicit (ADI) scheme. Preliminary calculations have been made for the flow in a rectangular combustion chamber with a discrete distribution of inlet injection ports employing an algebraic turbulence model with an ad hoc specified mixing length distribution. The more recent computations including the two-equation turbulence model are presently being carried out and progress to date will be discussed.

However as part of the EPA sponsored program referred to earlier, extensive flow field and chemical species measurements have been made in an axisymmetric research combustor at UTRC by Bowman, Owen and Spadaccini. Analagous measurements have not yet been made in a simple three-dimensional combustor, but the need for such detailed information is quite critical. Recent results obtained with the axially symmetric code using a two-equation turbulence model show the extreme sensitivity of the flow predictions to the inlet flow conditions, for instance the assumed radial velocity profile at the air inlet dump plane in the coaxial jet combustor under consideration had a major impact on the flow predictions. Since the inlet radial velocity profile is not normally available as part of the known inlet conditions, the implication is clearly that in future studies either the inlet radial profile of velocity must be measured or the calculation started from some inlet plane where this radial velocity is indeed

either known precisely or negligibly small. The importance of attention to computational detail and the major effects on the predicted flow fields of such items as the treatment of corner points and the so-called wall function technique of approximating the wall boundary layer are clearly illustrated by the two-dimensional predictions and comparison with measurements. Unfortunately, the detailed experimental data available for three-dimensional research combustors is almost nonexistent, hence the results of the comparison of prediction and experiment are even more difficult to assess than in the comparatively well documented axially symmetric case. Nevertheless, the three-dimensional calculations seem to show that the qualitative characteristics of the jet expanding into the combustor are represented quite reasonably. As one proceeds away from the inlet, the jet spreading is evident and reverse flow is clearly present behind the inlet-plane wall regions. Due to the large inlet velocity and the relatively small number of grid points (17x9x17 grid) employed in the calculation, cell Reynolds numbers in the axial direction became large so that significant truncation errors due to artificial viscosity are almost certainly present in the results. In addition, the equilibrium hydrocarbon chemistry assumption was not expected to be valid near the inlet port of the combustor under consideration. Therefore, an ad hoc ignition delay criterion was imposed on the solution to prevent unrealistically large temperature gradients from occurring near the inlet. Even though the present numerical results are almost certainly inaccurate, both the basic integrity of the computational procedure developed under the present program and the capability of the MINT code to perform calculations of three-dimensional combusting flows with recirculation have been demonstrated. The above considerations do, however, point out the need for both difference formulae which are accurate when very rapid, almost discontinuous changes in the dependent variables occur, and nonequilibrium chemistry models suitable for inclusion in a coupled fluid mechanics computer code.

To summarize, the two-dimensional predictions carried out at UTRC show considerable promise, but also clearly demonstrate the need for the combination of rigorous, painstaking attention to detail and complete information on inlet and boundary conditions. The three-dimensional predictions have established the feasibility of making simple time-dependent combustion calculations in three space dimensions, but point out the problem of, from an industrial point of view, long computer run times that result in three dimensions even with highly efficient numerical methods.

ABSTRACT

Experimental Investigation of Acoustic-Kinetic
Interactions in Non-Equilibrium H_2-Cl_2 Reactions[*]

by

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It has long been recognized that the coupling between chemical
kinetics and acoustic wave propagation may be instrumental in the growth
of small pressure disturbances which eventually lead to the non-linear,
large-amplitude instabilities often observed in practice. Considerable
insight into this phenomenon has already been obtained in several
theoretical studies [1, 2, 3, 4]. In one of them [1], sound propagation
in an infinite, irreversibly reacting medium was considered for the case
of a simple one-step reaction with Arrhenius kinetics. Substantial
amplification of the pressure fluctuations, as high as 300 to 400% under
certain conditions, was predicted for exothermic reactions. Based on this
type of analysis, extensive theoretical results have been obtained, especial-
ly in regard to sound scattering and acoustic energy considerations [4].
Yet, to the knowledge of the authors, no systematic experimental investiga-
tion of this phenomenon has been reported so far; hence the motivation for
this work.

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[*] Reference [5].

Experiments of sound propagation in a non-equilibrium hydrogen-chlorine reacting mixture were conducted in a 5.5 m-long, 8 cm-diameter Pyrex tube. The photochemical reaction between H_2 and Cl_2 is initiated by UV radiation incident onto the premixed, homogeneous reactive mixture. The overall reaction is measured by monitoring the quantity of UV light absorbed by molecular chlorine and the mean temperature of the gas phase by means of a resistance thermometer. Sound waves are generated at one end of the tube by means of a shaker-piston arrangement, in the form of a 2-cycle burst of a given frequency and monitored by means of several microphones strategically placed along the tube. The incident burst subsequently reflects back and forth at both ends of the tube and as a result, one is able to examine a specific acoustic wave during a time interval as long as 0.2 to 0.3 second, before its amplitude reaches the noise level due to sound absorption.

Amplification of the sound pressure fluctuations due to acoustic-kinetic coupling was consistently observed throughout this investigation at different acoustic frequencies and for different H_2-Cl_2-Ar mixture compositions. Analysis of the experimental results shows that the observed rate of amplification is typically three times larger than what would be expected from simple consideration of conservation of acoustic energy, thus indicating that the contribution of the acoustic-kinetic coupling effect to the net sound amplification is very significant (total amplifications of up to 60% of the initial sound amplitude were commonly observed over the sound residence

time-interval). Within experimental error and also within the uncertainty attributed to the determination of the overall Arrhenius parameters m and β (determined for each test by fitting the observed chlorine concentration and mean temperature histories to an Arrhenius expression), it is found that the instantaneous rate of sound pressure amplification   depends on the instantaneous experimental value of the expression

$$\frac{1}{2\gamma T_o(t)} \frac{dT_o}{dt}(t) \left\{ m + \frac{\beta(\gamma-1)}{T_o(t)/T_{o,in}} + \gamma \right\}$$, regardless of the sound frequency

and mixture composition or pressure. This is in agreement with the theoretical predictions of the quasi-steady model. This result is also consistent with the observation that the present experimental investigations was conducted in the quasi-steady interaction regime.

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RESEARCH NEEDS IN ALTERNATE FUEL COMBUSTION

By

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Between 1973 and the present time, the cost and availability of aircraft jet fuels have drastically changed. Per-gallon jet fuel costs have more than tripled for both commercial and military consumers. Fuel procurement actions have encountered difficulties in obtaining desired quantities of fuel, even though significantly reduced from 1972 consumption levels. These developments have encouraged initial examinations of the feasibility of producing jet fuels from non-petroleum resources.

Although contemporary problems of economics and supply are primarily responsible for the recent interest in new fuel sources, long range projections of available world-wide petroleum resources also indicate the necessity for seeking new means of obtaining jet fuel. Regardless of near term problems, the current dependence on petroleum as the primary source of jet fuel can be expected to cease sometime within the next half century.

If the general nature of future aircraft (size, weight, flight speed, etc.) is to remain similar to existing designs, liquid hydrocarbons can be expected to continue as the primary propulsion fuel. Liquified hydrogen and methane have been extensively studied as alternatives but seem to be feasible only for very large aircraft. The basic non-petroleum resources from which future liquid hydrocarbon fuels might be produced are numerous. They range from the more familiar energy sources of coal, oil shale, and tar sands to possible future organic materials derived from energy farming. Experience to date indicates that basic synthetic crudes, especially those produced from coal, will be appreciably different than petroleum crude. Reduced fuel hydrogen content would be anticipated in jet fuels produced from these alternate sources.

Because of the global nature of aircraft operations, jet fuels of the future are likely to be produced from a combination of these basic sources. Production of fuels from blends of synthetic crudes and natural crudes may also be expected. In light of the wide variations in materials from which world-wide jet fuel production can draw, it is anticipated that economics will dictate the acceptance of future fuels with properties other than those of currently-used JP-4, JP-5, and Jet A. Much additional technical information will be required to identify fuel specifications which provide the optimum solution to the following objectives:

a) allow usage of key world-wide resources to assure availability

b) minimize the total cost of aircraft system operation

c) avoid sacrifice of engine performance, flight safety, or environmental impact.

A complex program is necessary to establish the information base from which future fuel specifications can be made. Figure 1 depicts the overall nature of the required effort. Fuel processing technology will naturally be of primary importance to per-gallon fuel costs. The impact of reduced levels of refining (lower fuel costs) on all aircraft system components must be determined. These include fuel system (pumps, filters, heat exchangers, seals, etc.), and airframe (fuel tank size and design, impact on range, etc.) considerations as well as main burner and afterburner impacts. In addition, handling difficulties (fuel toxicity) and environmental impact (exhaust emissions) require evaluation. The overall program must be integrated by a system optimization study intended to identify the best solution to the stated objectives.

This abstract reviews the aspects of combustion system and environmental impact from the standpoints of problem definition, projected approaches, and research needs.

A. Fuel Effects on Combustion Systems

Although future fuels may affect combustion system/engine performance and design through variations in volatility, viscosity, and concentrations of olefins, sulfur, and trace metals, changes in hydrogen and nitrogen content are expected to be the primary impacts.

Fuel hydrogen content is the most important parameter anticipated to change significantly with the use of alternate fuels. In most cases, reduction in fuel hydrogen content would be due to increased concentrations of aromatic-type hydrocarbons in the fuel. These may be either single ring or polycyclic in structure. Experience has shown that decreased hydrogen content significantly influences the fuel pyrolysis process in a manner which results in increased rates of carbon particle formation. The particulates are responsible for the formation of a luminous flame within the combustor and increased exhasut smoke emission.

The additional radiative loading on combustor liners due to decreased fuel hydrogen content can be substantial. The resulting increases in combustor liner temperature translate into decreases in hardware life and reliability. Figure 2 illustrates the sensitivity of combustor liner temperature to hydrogen content. This data, representative of older engine designs, is correlated by a non-dimensional temperature parameter:

$$\frac{T_L - T_{LO}}{T_{LO} - T_3}$$

The numerator of this expression represents the increase in combustor liner temperature, T_L, over that obtained using a baseline fuel (14.5% hydrogen JP-4), T_{LO}. This is normalized by the difference between T_{LO} and combustor inlet temperature, T_3. It should be noted that this parameter is representative of the fractional increase (over the baseline fuel) in heat transfer to the combustor liner resulting from usage of a non-standard fuel.
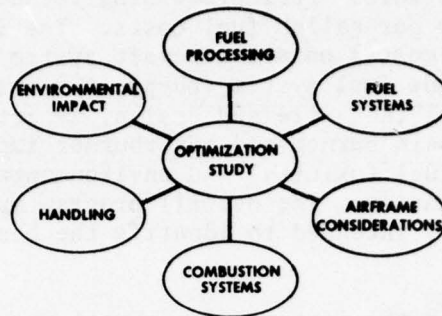
89

Figure 1. Overall Scheme for Alternate Jet Fuel
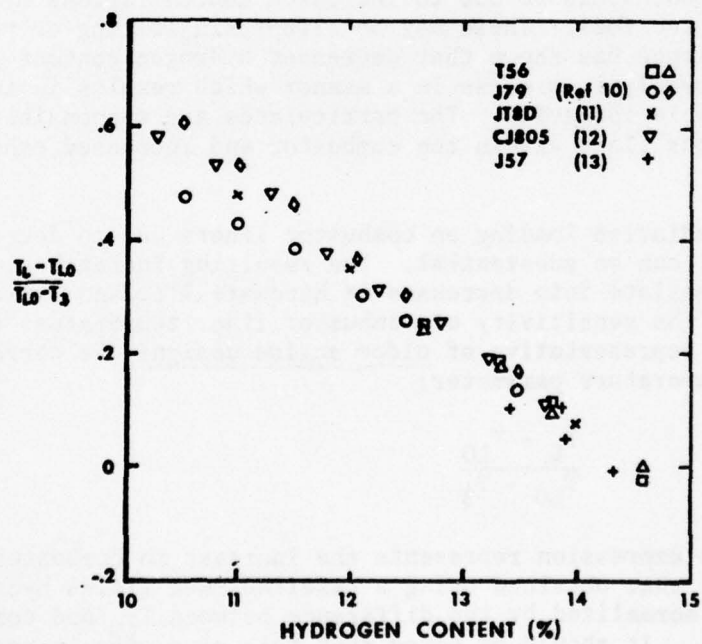Development Program.

Figure 2. Liner Temperature Correlation for Many
Combustor Types.

Because engine smoke characteristics are extremely sensitive to combustor design details, differences in emission are not correlatable in the same manner as combustor liner temperature. However, results obtained using a T56 single combustor rig at AFAPL are illustrative of typical trends (see Figure 3). Significantly increased smoke emission is evident with decreased hydrogen content for each condition tested. Trends between smoke emission and hydrogen content are similar for each operating condition. Increased absolute smoke emission between the 394°K and 644°K combustor inlet temperature conditions is attributable to increased pressure and fuel-air ratio. Although a further small increase might be expected for the 756°K condition because of higher pressure, the lower fuel-air ratio required to maintain 1200°K exhaust temperature (a facility limitation) results in a lower absolute smoke emission.

The effect of increased fuel bound nitrogen is evaluated by determining the additional NO_x emission occurring when nitrogen is present in the fuel and calculating the percent of fuel nitrogen conversion to NO_x necessary to cause this increase. The baseline petroleum fuels currently used have near zero (<10 ppmw) fuel nitrogen. Results presented in Figure 4, obtained using pyridine fuels, indicate the importance of two variables. First, as combustor inlet temperature is increased, conversion is reduced. Secondly, as fuel nitrogen concentrations are increased, conversion decreases. This second trend is consistent with available results for oil shale jet fuels which had less than .08% nitrogen. It should be noted that the NO_x increases associated with the levels of fuel nitrogen in synthetic jet fuels produced to date (less than .08%) represent only a small increase in NO_x emission (<10%). In fact, synfuel results are shown as a band in Figure 4 because of difficulties in accurately measuring small emission increases.

B. Combustion System Design Approaches

Although currently in the early stages of assessment, it appears certain that future combustion system designs will be significantly influenced by the changing character of fuel properties as alternate energy sources are tapped. Most importantly, designs must be developed which will accommodate lower hydrogen content fuels without the combustor liner temperature and smoke emission problems noted above while maintaining the customary level of combustion system performance.

Lean primary zone combustion systems, which are much less sensitive to fuel hydrogen content, will comprise a major approach to utilizing new fuels. Low smoke combustor designs have already been shown to be much less sensitive to fuel hydrogen content. Figure 5 compares the correlation for older comubstor designs (Figure 2) with results for a newer, smokeless design. Current development of staged combustion systems will further contribute towards achieving the goal of leaner burning while maintaining desired system performance. Some of these designs have been shown to function nearly independent of fuel type.

It is also possible that new, novel approaches can be developed and applied to overcome alternate fuels related problems. For example, catalytic combustion may be utilized to promote lean burning to preclude many of the difficulties discussed above. This concept, to be discussed in additional detail in another AFAPL presentation, has demonstrated the capability of stable, efficient combustion at lean fuel-air ratios extending below the flammability limit.
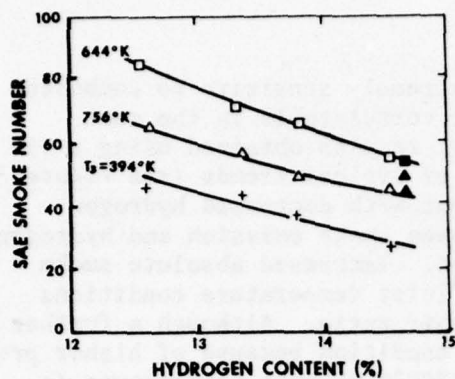
91

Figure 3: Smoke Emission Dependence on Hydrogen Content.

Figure 4: Fuel Bound Nitrogen Conversion to NO_x in an Aircraft Gas Turbine Combustor.
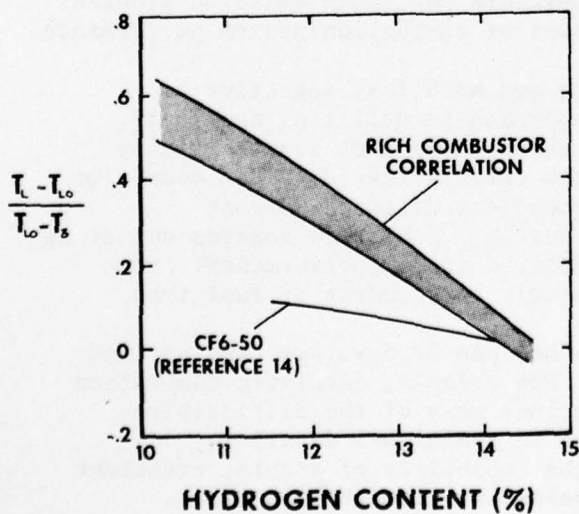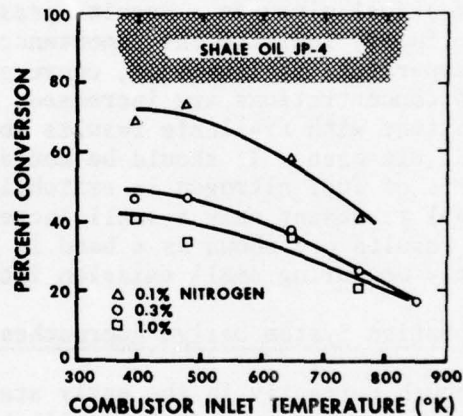

Figure 5: Effect of Lean Operation on Combustor Liner Hydrogen Content Sensitivity.

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C. Research Needs

A number of fundamental research topics are vital to the future effective utilization of alternate jet fuels. These items include:

a) Improved understanding of practical hydrocarbon fuel pyrolysis leading to the ability to include gross fuel chemistry effects in combustor analytical models.

b) Development of particulate formation models which allow variations in fuel chemistry and pyrolysis processes (the results of a) in predictions of combustion zone parameters.

c) Enhanced modeling capability to include prediction of fuel effects on combustor radiant loading, smoke emission, ignition and stability.

d) Inclusion of fuel effects in afterburner IR modeling.

e) Characterization of preignition and flashback as potential problems in future prevaporization/premix systems.

f) Development of new fuel test/characterization methods or improved relationships between present fuel test methods and actual engine combustion characteristics.

g) Evaluation of methods of relating combustion system data to final management information (i.e., combustor liner temperature to life, durability, and cost).

Beginning 1 October 1976, AFAPL will begin a combustion research program which addresses some of the above research needs. Specifically needs a and c above will be supported. A program will be initiated to develop quasi-global reaction mechanisms for fuel pyrolysis (to $CO + H_2$) for six major jet fuel components -- n-paraffins, iso-paraffins, cyclo-paraffins, single ring aromatics, double ring aromatics, and partially saturated aromatics. This effort will be supported by analytical and experimental in-house efforts to implement findings into usable tools for alternate fuels/combustor evaluations. A simplified combustor geometry will be analyzed using available models with the new quasi-global mechanisms as inputs. Empirical evaluations of the same combustor geometry with variations of fuel type will be undertaken using the AFAPL Combustion Tunnel (currently under construction) to verify the model results.

RESEARCH NEEDS IN CATALYTIC COMBUSTION

By

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Background

A catalytic combustor is a device in which chemical reactions initiated by a heterogeneous catalyst (i.e., catalytic surface) play an important role in the energy release process. The role of the catalyst makes high values of surface area per combustor volume desirable. Pressure drop through the catalyst bed must be minimized. Therefore, the combustor is primarily constructed from a monolithic material, with ceramic honeycombs being leading candidates. The catalyst is deposited on all exposed surfaces.

A honeycomb combustor acts as a bundle of tubular reactors with the energy release occurring as the reactants flow down each tube. Therefore, the temperature rise is monatonic, with the maximum temperature achieved at the combustor exit. Mass is not transferred between tubes although conductive heat transfer through common walls will occur. The principle energy input to each tubular reactor results from the combustion within the duct. Therefore, to a first approximation, each reactor operates independently from the others. If the reactors are identical, both from geometrical and chemical activity points-of-view, the energy distribution across the combustor inlet plane will be preserved. That is, if the inlet flow has a uniform distribution of temperature, composition and velocity, then the exit plane will display uniform distributions of these quantities. Similarly, any particular inlet profile will emerge from the combustor exit.

There are several mechanisms which occur in the catalytic combustor. The reactants must diffuse to the catalyst and be adsorbed. Surface chemical reactions occur, followed by desorption and diffusion of the products into the bulk flow. Homogeneous gas-phase reactions are also present. The energy release controlling mechanism changes as the reactants flow along the tube, as depicted in Figure 1. At the inlet, the gas temperature is too low for significant gas-phase reactions; the lower activation energy surface reactions control. As the temperature increases, the heterogeneous reaction rates increase to a point of being rapid as compared with the reactant diffusion rates. Thus, over a large portion of the duct, turbulent mass transfer limits the rate of energy release. Ultimately, the temperature has increased sufficiently for gas-phase reactions to dominate. For most operating conditions, the transition from surface reaction to mass transfer control occurs within one tube diameter of the inlet. The transfer from reactant diffusion to gas-phase reaction control occurs at approximately 1800°F. Since current aircraft gas turbine combustors produce exit temperatures up to 2500°F, a portion of the catalytic combustor need not have any catalyst; gas-phase reactions are controlling.

There are three primary components of the catalytic combustor--catalyst, catalyst support or substrate, and fuel/air carburetion system.

Although the catalyst does not exist as a separate entity (it is deposited on the substrate), its important role justifies its consideration as an individual component. The field of catalysis is large and complex; countless catalysts exist. Historically, however, catalysts have been principally used for synthesis considerations - hydrogenation, dehydration, reforming, isomerization, etc. Essentially no effort has been made to optimize catalysts for the total oxidation of hydrocarbons. Of the currently available materials, platinum is the leading catalyst candidate.

The bulk of the combustor is constructed from the catalyst support. Metal substrates (i.e., high nickel alloys) are receiving attention but, due to a thermal expansion mismatch, a sustained adhesion of the catalyst on the substrate has not been proven. Therefore, ceramic substrates (e.g., cordierite, silicon nitride) are leading candidate materials. There are several factors to consider in choosing a substrate, including: surface area, porosity, inertness, stability, strength, thermal expansion, etc. The first two are important in maximizing the total active area - including the interstitial area. The substrate should not react with the catalyst, nor should it experience a phase change over the operating temperature range. Thermal expansion considerations are important to assure adhesion and to prevent failure due to thermal shock.

The third component, a fuel/air carburetion system, is required to provide a prevaporized, premixed inlet flow to the combustor. Achieving uniform temperature, velocity and composition profiles are important for the reasons discussed previously. The required degree of fuel vaporization has not yet been established but will be investigated in future programs. It is likely that large amounts of liquid fuel would adversely affect the catalyst, although good performance was attained in an AFAPL feasibility test where between 5% - 10% of the fuel was not vaporized.

Three published studies affirming the feasibility of catalytic combustion at simulated high power, gas turbine engine operating conditions have been performed. In general, the results from the three studies were similar - a combustion efficiency at conditions typical of a high power, gas turbine engine operation of 100% could be attained. Data from the AFAPL investigation, which used JP-4 while the other studies employed propane, can be taken as representative. Figure 2 displays the variation of combustion efficiency with fuel/air ratio for an inlet temperature of 710°F. Two observations can be made:

1. Complete combustion at fuel/air ratios outside the normal flammability limits can be attained. As shown on the graph, 100% conversion was achieved for mixtures leaner than the normal, lower flammability limit.

2. The performance of the combustor is sensitive to inlet temperature, particularly at low fuel/air ratios.

It should be emphasized that no attempt was made to optimize the combustor used in this study. Performance improvements (i.e., lessening the temperature sensitivity) are anticipated as the concept is developed.

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Applications

The fundamental concepts motivating the application of catalysts to gas turbine engine main burners and afterburners are explained in AIAA Paper 76-46 presented at the 14th Aerospace Sciences Meeting, January 1976. The requirements of the combustor components were outlined, as were the potential problem areas and the initial data available to address them. The advantages resulting from the application of the concept were shown to be substantial. Although the interested reader would benefit from reviewing the referenced manuscript, the following summary is offered.

Structural considerations of the turbine blades currently limit the maximum turbine inlet temperature to 2500°F which, in turn, places a restriction on the overall fuel/air mixture ratio (f) of approximately $f < 0.028$ for JP-4 type fuels. Such compositions, however, are not within the flammability limits. Therefore, the conventional and many future combustor designs employ several zones of combustion. In each reacting zone, the air-flow is throttled to produce a local f greater than the overall value to ensure combustibility. Associated with the more fuel rich regions are higher temperatures, in some cases exceeding 4000°F. Downstream dilution zones mix in the remaining air to reduce the overall temperature to acceptable levels. The thermodynamics and fluid mechanics of such combustors lead to unsteady, skewed combustor exit temperature profiles. As well, the high temperature regions favor the formation of carbon particles, increase the radiant heat transfer to the combustor and turbine components, and produce high NO_x exhaust emissions.

The catalytic main burner, because of high chemical activity of the catalyst, can combust at the overall fuel/air mixture. A maximum combustor temperature of 2500°F occurs at the exit. Additionally, the tubular character removes the large turbulent fluctuations associated with conventional systems. Since each reactor operates independently, the inlet temperature profile is reflected directly in the exit profile. Therefore, optimal turbine inlet temperature profiles could be obtained, with a net effect of an increase in its overall value. Preliminary engine cycle calculations indicate that for a 100°F increase in this temperature, for engines of fixed thrust and size the static SFC reduces by 12%, while for engines of specified SFC the static thrust per air weight-flow increases by 3%. It is noted that due to the presence of the substrate in the reacting flow, the catalytic unit has a heat capacity 500 times greater than a conventional system, enhancing its stability characteristics. As well, the low temperature zones associated with the catalytic combustor decrease the tendency to form carbon particles, reduce the radiative heat transfer by up to 80%, and suppress NO_x exhaust emissions by two orders of magnitude.

Catalytic materials can be used in the afterburner to improve the ignitor and flameholder. The ignitor application is straight-forward; the high chemical activity of these materials, if they are located in a locally controlled f, should ensure high reliability. Thus, a separate AB spark system would not be required. The catalytic flameholder acts to promote the axial rate of energy release in the AB. That is, at any given axial position, a greater portion of the chemical energy contained in the reactants has been

released. Either of two approaches can be taken to achieve the accelerated rate. First, if catalysts are located to promote the initial processes (fuel reforming, initial oxidation reactions, etc.) then a higher rate could be achieved. Selective catalyst-coating of conventional hardware may achieve this goal. The influence of the catalyst may, however, be confined to the boundary layer over the device. Second, if the size of the sources of the combustion (flameholder width) could be increased without increasing pressure losses, the sources would merge at shorter downstream distances, filling the AB cross-section with reaction. Thus, a greater distance remains before the AB exit to completely consume the fuel and release the energy. The use of an annular ring of honeycomb material would permit increases in flow blockages without prohibitive increases in pressure loss. The device would be coated with catalyst, substituting a catalytic initiation for the traditional fluid mechanical residence time ignition.

Fundamental Concerns

While the principle AFAPL programs are pursuing the application aspects of catalytic combustion, a need exists to investigate several related fundamental concerns, including:

a) products of catalyzed reactions, and their role in the total energy release;

b) transfer of the energy release controlling mechanism;

c) processes responsible for chemical and physical degradation of catalyst systems;

d) unsteady, catalytic combustor modeling;

e) influence of liquid fuel impingement on catalytic surfaces;

f) flame stabilization in the presence of a catalyst for both bluff and porous bodies.

Beginning in FY77, in addition to developing the applications of catalytic combustion, AFAPL will be involved in some of the above fundamental concerns. Particularly experimental investigations of items (b) and (f) will be performed.
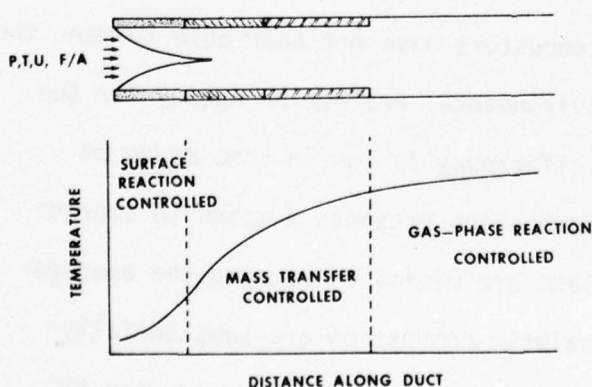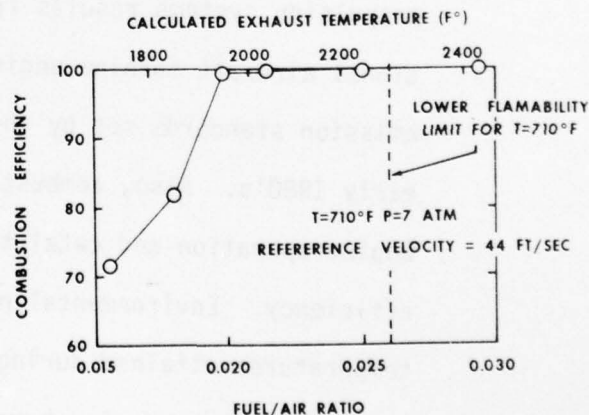

Fig. 1. Controlling Mechanisms.

Fig. 2. Catalytic Combustion at Simulated High Power.

ASSESSMENT OF CATALYST TECHNOLOGY FOR CATALYTIC COMBUSTION

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Catalytic combustion has been known since the early work of Sir Humphrey Davy over 150 years ago when he discovered that platinum wire could catalyze combustion reactions in flammable mixtures, and that these reactions occurred with no apparent flame and with high radiative fluxes. This concept has found only limited commercial application since Davy's early experiments. However, over the last few years, there has been an increasing interest and activity in developing catalytic combustion for commercial applications such as residential heating systems, commercial and industrial boilers, stationary gas turbines, process furnaces, supercharged boilers and air-breathing propulsion systems. The present discussion will focus on the latter.

The motivation to develop catalytic combustion for air-breathing propulsion systems results from the fact that modifications to conventional aircraft turbine engine combustors have not been able to meet the emission standards set by the Environmental Protection Agency for the early 1980's. Also, combustion efficiency is low in some modes of engine operation and catalytic combustion presents a means to improve efficiency. Environmental problems are minimized because the average temperatures attained during catalytic combustion are substantially lower than those during homogeneous combustion, thereby reducing NO_x formation by the fixation of nitrogen. Unburned hydrocarbons and carbon monoxide are also substantially reduced by catalytic oxidation. Increased efficiency of operation results because catalytic combustors can operate

over extended fuel to air ratios, even out of the fuel flammability
limits.

There are a number of critical constraints which must be met in
the operation of a catalytic system. These include adequate activity,
low pressure drop, and extended catalyst life. The latter parameter
is perhaps the most difficult to meet since the systems of interest
operate at unprecedented high temperatures for conventional catalysts,
usually between 2000 and 2600°F. Most catalytic materials sinter
severely at these temperatures, and therefore lose surface area and
mechanical strength.

Substantial advances have been made over the last several years in
the synthesis of catalysts which meet these constraints. For example,
it is now possible to commercially manufacture high temperature honey-
comb ceramic structures which can be used as substrates for catalytic
combustion. These ceramics can operate at temperatures varying from
2200°F (cordierite) to 3000°F (silicon carbide). Recently developed
techniques in inorganic chemistry enable the catalytic chemist to prepare
washcoats which are thermally stabilized and maintain adequate surface
area for catalysis in the same temperature range. Other concepts such
as catalyst-support interactions permit thermal stabilization of the
catalytic surface and thereby minimize sintering of the catalytically
active species.

In this presentation, problems associated with the catalysts used
for catalytic combustion in air-breathing propulsion systems will be
discussed, and the application of advances in catalysis and related dis-
ciplines to the solution of these problems will be reviewed.

Abstract

DESIGN CRITERIA FOR CATALYTIC COMBUSTORS

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Predictions which demonstrate the variation of catalytic combustor performance with (1) bed geometry, (2) bed material, and (3) initial gas conditions (i.e. preheat temperature and mass flow rate) are presented. The formulation and numerical techniques applied in the predictive procedure are also briefly discussed. Based on predictions, a novel catalytic combustor system design concept is suggested.

Catalytic combustion in a honeycomb monolith is a complex process which involves the interaction of several physical and chemical phenomena. Of primary importance are (1) radial heat and mass transport between the gas and wall, (2) axial heat and mass transport in the gas, (3) axial radiative and conductive wall heat transfer, (4) heterogeneous surface and bulk gas phase kinetic reactions. The coupling of these phenomena determines bed performance in terms of maximum throughput, maximum bed temperature and fuel conversion efficiency. An efficient, yet adequate, numerical technique, which includes all of the abovementioned phenomena, has been developed to establish the variation of bed performance with bed parameters. The

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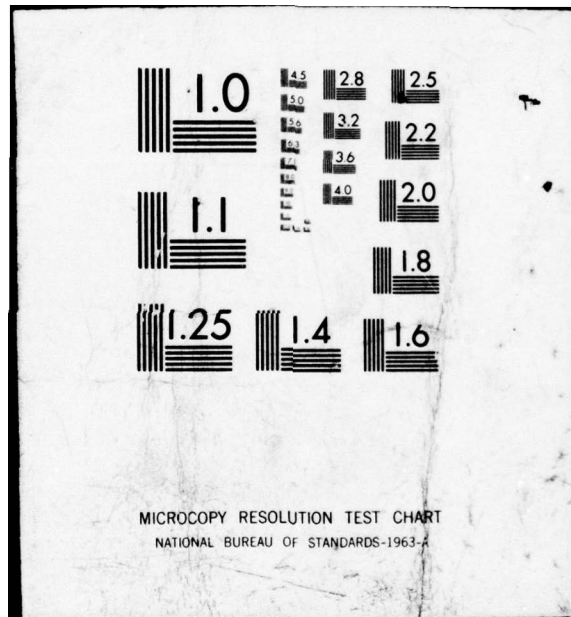
technique utilizes matrix procedures to solve the finite difference form of the governing partial differential equations. The axial distribution of both wall and bulk gas properties and wall temperature are output by the code. The solution procedure is reliable and stable for the range of input parameters utilized to date.

Code predictions indicate that (1) maximum throughput levels increase as channel diameter, bed conductivity and surface reactivity increases, (2) maximum bed temperature decreases as conductivity increases (3) complete fuel conversion requires the activation of homogenous gas phase reactions. These preliminary observations have significant system design implications.

Based on predictions made during this study a catalytic combustor design is suggested which utilizes a bed front end with large diameter channels and a bed back end with small diameter channels. The large front end channels permit bed operation at large throughputs while the small channel back end prevents breakthrough (i.e. poor fuel conversion efficiency). Through experimental testing, this design has been found to give good performance with methane and propane fuels. In the near future additional analysis and experimental work will be undertaken to further establish the value of this and other novel system design concepts.

EXPERIMENTAL AND THEORETICAL ASPECTS OF
HYBRID CATALYTIC COMBUSTION

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Exxon Research and Engineering Company

Current jet engine designs will not meet the EPA Aircraft
Emissions Limitations for NO_x, unburned hydrocarbons (UHC), and CO
emissions that will be in effect January 1, 1983. NO_x emissions
are particularly difficult to control at high power operation where
they tend to peak as a result of the high temperature and near
stoichiometric combustion conditions encountered in the primary
zone of conventional jet engine combustors. UHC and CO emissions,
on the other hand, are greatest under engine idle conditions when
the temperatures are lowest and the gas mixing is poorest.

Catalytic combustion, operating with very lean air-fuel
mixtures, has been proposed as a possible means of reducing gas
turbine engine emissions to very low levels. Studies reported by
AFAPL and NASA indicate that these goals can be met at conditions
characteristic of high power engine operations. However, idle power
conditions provide a more severe test of this system from the stand-
point of ignition and high efficiency combustion. Thus, in awarding
contract No. F33615-75-C-2033 to Exxon Research and Engineering Company
on February 1, 1976, the Air Force sought to determine how such a
system could be configured and operated to produce acceptable results
at low power settings.

The Exxon program was divided into three phases over 15 months.
Phase I involved a detailed literature and theoretical analysis of the
available information. It thus provided the basis for selecting catalysts
to be supplied, or fabricated by catalyst or substrate manufacturers, from
among currently existing materials.

A number of experiments were conducted in Phase II to see if
there were any catalysts capable of igniting JP-4/air mixtures near the
400 K temperature experienced at low power jet engine operation. As we
had suspected, there were none. The rest of the program, therefore,
focused on the hybrid system approach. For this hybrid system, we built
and completely characterized the non-catalytic fuel/air pre-burner. Then,
we completed a three-part preliminary catalyst screening task. Part 1
ranked catalyst activity as a function of temperature and surface to
volume ratio of seven Pt/Pd catalysts deposited on a single substrate
composition of varying geometry. Part 2 evaluated various substrates
and wash coat materials on which noble metal catalytic materials had
been deposited, with respect to diffusion-induced reaction limitations

and pressure drop. The most promising catalysts (composition and substrates) were ranked in Part 3 in order to choose the catalysts most applicable in the idle mode operation. The two best systems were subjected to 20 hrs. each of confirmation tests prior to scaled-up fabrication in Phase III of the program. The total number of experimental test hours logged was in excess of 100, and the number of catalyst-substrate combinations tested was in excess of 25.

The two best catalytic combustor system designs are being fabricated in the size required for operation at a 0.6 lb_m/sec air. In addition to delivery of these two systems, a system safety evaluation will be provided. A final report draft detailing all results and conclusions from this program is currently being completed.

The test results obtained in Exxon's Hybrid Combustor showed that 99.9% combustion efficiency was achieved at a catalyst inlet temperature of 1200 K, for a reference velocity of 26 m/s, and a pressure of 376 kPa when a Pd or Pt/Pd catalyst was used. The CO and UHC conversions through the better monolithic supported catalyst beds were in excess of 90 and 95%, respectively. The CO and HC concentrations at the inlet to the catalyst were in the range of 450 and 350 ppm, respectively. The equivalence ratio in the primary combustion zone was about 1.5 and the overall equivalence ratio after secondary air addition was 0.30. The formation of thermally generated NO_x in the primary combustion zone was minimized by maintaining a rich mixture as evidenced by a NO_x concentration of 20 to 30 ppm at the catalyst bed inlet. However, the NO_x concentration increased to about 40 ppm at the catalyst exit, presumably by the oxidation of nitrogen containing reduced combustion products, i.e., HCN and NH_3. Because of the low concentration of combustibles in the gas stream at the inlet to the catalyst, there was no measurable temperature rise across the catalyst which was 20.32 cm long and 5 cm diameter. The increase in NO_x concentration across the catalyst bed, even though the gas temperature across the bed did not increase, has been observed in all catalysts tested.

Table 1 summarizes the results of the catalyst screening tests in the Hybrid Combustor at constant catalyst inlet temperatures, pressures, and velocities. The UHC and CO conversion data show that in nearly all cases the oxidation of CO was slower than the conversion of hydrocarbons. The average residence time of the gas stream in the catalyst bed was 2-3 ms. This table also shows that for a constant noble metal loading (1.7 kg/m³ of catalyst), the UHC and CO conversions can be correlated with the geometrical surface/volume ratio of the support. The surface/volume ratio varied from 996 to 2473 m²/m³ depending upon the geometry. In one case, a silicon carbide 0.31 cm diameter round (actually elliptical) hole monolith was tested, and surprisingly gave higher CO and UHC conversions than the 0.31 cm diameter round hole cordierite support. Another interesting aspect of the SiC support was that its response to temperature changes was much more rapid than that of cordierite. This

result is not surprising because of great differences in thermal conductivity, density and heat capacity of SiC compared to cordierite. Similar observations were made with catalyst QF which was supported on a corrugated metal substrate.

The activity of the catalysts is very temperature dependent. The highest activity, at 850 K, of all the catalysts tested was obtained for a 3.29 kg/m^3 loading of Pd on stabilized Al$_2$O$_3$ supported by a monolithic cordierite structure. This catalyst is identified as KQ in the table. CO and UHC conversions at 850 K were determined to be 75 and 83%, respectively, compared to 91 and 96%, respectively, at 1200 K.

Generally, the Pd on Al$_2$O$_3$ catalysts were more active than the Pt/Pd catalysts, while the rare earth oxide (REO) catalysts were found to be least active. Pd promoted by base metal oxide catalysts (KU) seemed to be more active initially compared to Pd catalysts, as evidenced by the great differences in CO and UHC conversions between catalysts KU and KP. Catalyst KP contained a 0.29 kg/m^3 loading on a ZrO^2 wash coat, whereas catalyst KU contained a Pd loading of 0.39 kg/m^3 on the same support which had a wash coat of stabilized Al$_2$O$_3$ in place of ZrO$_2$. The 28 kg/m^3 loading of a mixture of CuO, Cr$_2$O$_3$ and MnO$_2$ on catalyst KU had CO and UHC conversions of 83 and 92%, respectively, compared to catalyst KP which showed CO and UHC conversions of 34 and 11%, respectively. It is interesting to note that the CO conversion of catalyst KP was greater than the HC conversion. The CoO addition to catalyst KP or the ZrO$_2$ wash coat may have had an effect on CO conversions, since in all other catalysts tested, CO conversions were always lower than UHC conversions.

Twenty hour durability tests were conducted with catalysts KQ and QF which contain 3.29 kg/m^3 Pd on stabilized Al$_2$O$_3$, and > 5 kg/m^3 Pd on corrugated metal, respectively. Catalyst KQ is supported on a cordierite monolith with rectangular geometry having a surface/volume ratio of 2109 m^2/m^3. The KQ test was terminated after a total of 21 h of operation at 1200 K because the catalyst melted and fused due to an ignition problem. The catalyst activity decreased monotonically over the test period. Catalyst QF consists of > 5 kg/m^3 Pt on a stabilized wash-coated corrugated metal support that has an open area of 93%. Catalyst QF, on the other hand, maintained excellent activity throughout the 20 hour test.

During the durability tests, reaction rate data was obtained which was used to guide the design of the combustor being fabricated for delivery to the Air Force by September, 1976. The preliminary drawings of the deliverable system have been completed and sent to the Air Force for comments. The fabrication of the combustor is progressing on schedule in our machine shops.

A set of general catalytic combustion reactor modeling equations has been formulated and solved by computer. The equations include all the physical and chemical aspects of interest in a typical system. A steady state plug flow reactor is considered, with diffusional transport of

reactant species to the catalytic surface followed by catalytic combustion, heat release at the surface, and heat transport away from the surface. Simultaneous bulk gas phase combustion reactions, which are also included in the model, have presented no difficulty in the solution technique. Axial heat conduction within the monolith is also considered, but radiant heat transport is neglected for most cases considered thus far. The solutions obtained have qualitatively agreed with experimental findings and have indicated a number of important parameters, particularly gas velocity change which is ignored in many other modeling efforts. Further extension of the model is planned as well as a more extensive comparison between experiment and the model. The modeling effort was supported by Exxon and the NSF under the Summer Faculty Participation Program.

TABLE 1. RELATIVE CATALYST ACTIVITIES FOR METALS, (Σ 0.2%-0.3% ρ 370 W/c
AND 23.8 w/c REFERENCE VELOCITY (SPACE/INLET - 20.1 cm)

1976 AFOSR CONTRACTORS MEETING
AIR-BREATING COMBUSTION DYNAMICS

Air Force Aero-Propulsion Laboratory
Wright-Patterson AFB, Ohio

August 11-13, 1976

Mechanisms of High Temperature

Catalytic Combustion

(AFOSR 76-3052)

F. V. Bracco

Princeton University

Summary

Catalytic combustion is controlled not only by surface phenomena but
also by gas phase chemical reactions and turbulent transport processes
of mass, momentum, and energy. This is particularly true when honeycomb
(monolithic) substrates are used. A theoretical-experimental program is
considered which will eventually lead to the production and testing of
a two-dimensional model which accounts for all the controlling processes
and could then be used for optimal design of monolithic catalytic combus-
tors. The program is divided into two phases. In the first phase, an
isothermal boundary layer is considered with gas phase and surface reac-
tions of trace species only. The second phase includes the fully reactive
two-dimensional flow system. Methods of solutions of the equations are
discussed. The experimental program, which consists of measuring the com-
puted quantities, is to be carried out with a steady combustor and includes
the measurement of some stable and unstable species by a continuous argon
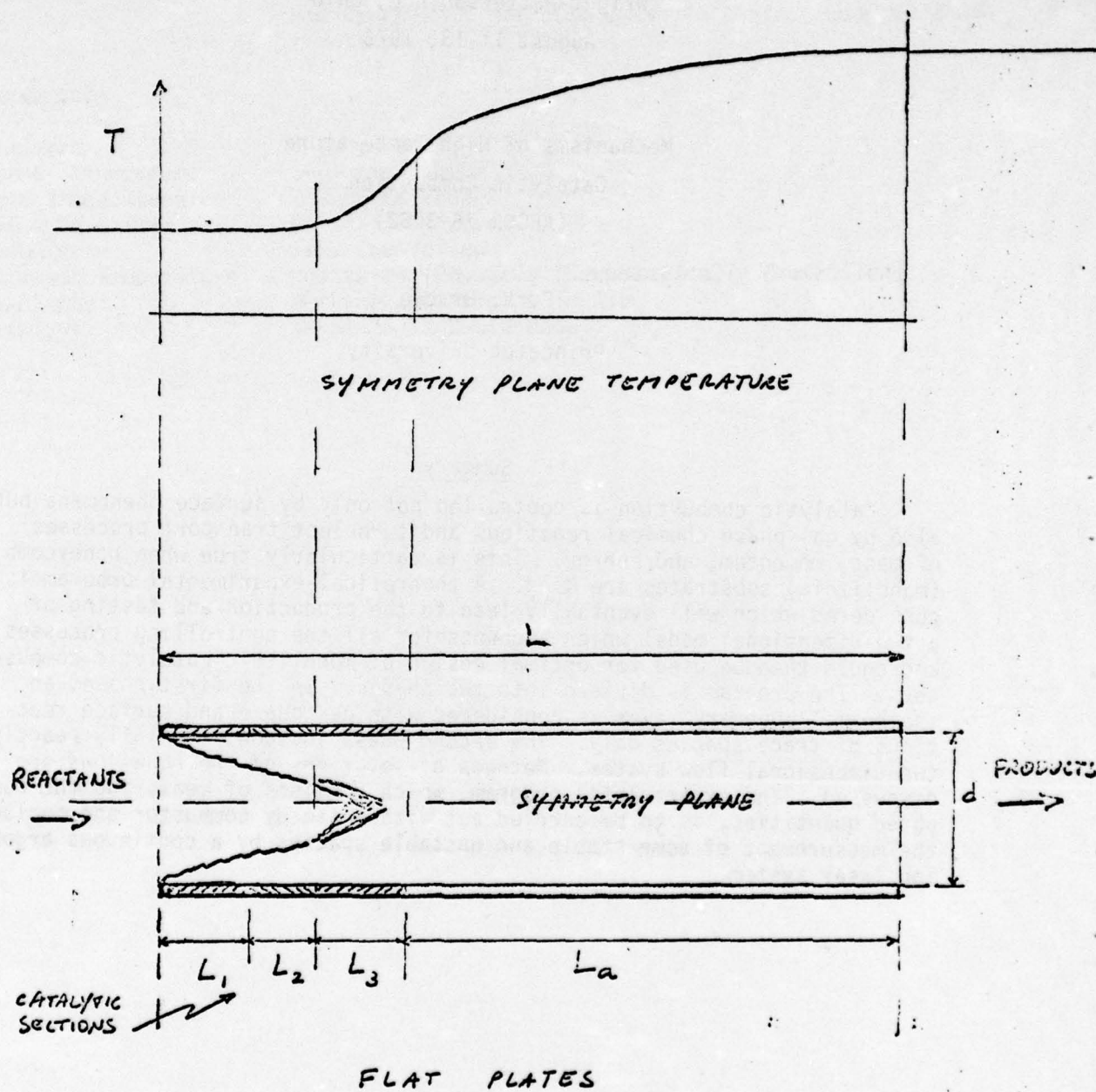ion laser system.

SYMMETRY PLANE TEMPERATURE

FLAT PLATES

FIGURE 1

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FIGURE 1

At the entrance, the reactants' temperature is generally too low for significant gas phase (homogeneous) reactions to take place, but they occur at the catalytic wall (heterogeneous reactions). Most likely, the complex hydrocarbon fuel molecule is absorbed and broken down at the surface where intermediates are formed and desorbed. Those intermediates diffuse out and react within the boundary layers (Catalyst L_1). Accordingly, the rate at which products are formed and heat is released in the boundary layers depend not only on the rate of the heterogeneous reactions but also on the rates of the homogeneous reactions and of the turbulent diffusion processes.

As heat is released, the temperatures of the gas and of the walls change. Homogeneous initiations reactions become faster, but heterogeneous reactions are still controlling. A different catalyst may now be more appropriate due to the changed wall temperature and gas composition (Catalyst L_2). Proceeding downstream, the temperatures of the gas in the boundary layers and of the catalytic walls keep increasing as more energy is released. At sufficiently high gas temperature, well below the exit temperature, gas phase initiation reactions become sufficiently fast to sustain massive homogeneous reactions within, or at the edge of, the boundary layers, perhaps still assisted by the catalytic walls. Different catalytic properties may again be desirable due to the changed gas and wall conditions (Catalyst L_3).

From this region on, gas phase reactions would be self-sustaining and additional catalytic surface may not appreciably speed up the achievement of equilibrium. Additional residence time is still needed and provided within the length L_a.

The above schematization, where the catalytic entrance serves as an ignitor, is by no means unique. In fact, different configurations are found if different characteristic scales are selected for the controlling processes and parameters, i.e., for gas and surface reactions, for the convective flow, for mass momentum and energy diffusion, and for L, d, L_1, L_2, L_3, and L_a.

The determination of the relative importance of the various parameter of catalytic combustion in monolithic combustors, and for various operating conditions, is the goal of the proposed theoretical-experimental program.

Phase 1:   Study of the tip of the boundary layer; isothermal gas
                            with surface and gas phase reactions of trace species
                            only.

Phase 2:   Study of the two-dimensional, fully reacting flow field;
                            non-isothermal gas with complete surface and gas phase
                            reactions.

Parameters

Pressure: 1 to 10 atm
Inlet Temperature: 300°F to 1000°F
Exit Temperature: 1800°F to 2800°F
Inlet Velocity: Up to 100 ft/sec
Turbulence: Grid Controlled
Catalyst Temperature: Monitored (Possibly Thermostatically Controlled)
Reactants: Methane and Propane in Air
Catalyst: Initially a Noble Metal

FIGURE 2

A Theoretical-Experimental Program

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FIGURE 2

A theoretical-experimental study of the symmetric flat plate configuration of Figure 1 is proposed. This configuration is selected primarily because it lends itself to the application of laser techniques. The analytical results will be obtained simultaneously for a cylindrical configuration which more closely resembles that of monolithic reactors.

In the first phase of the study, both theory and experiment will be applied to the entrance region i.e. to the tip of the reactive boundary layer (beginning of region L_1 of Figure 1). This region is important because it is here that intermediate trace species are first formed. It is also simpler to treat analytically (see Figure 3).

In the second phase, the fully reactive two-dimensional flow will be considered. Significant heat release will occur first in the boundary layer (rest of region L_1 and region L_2 of Figure 1) and then throughout the field (regions L_3 and L_a of Figure 1).

The parameters of the program are given in Figure 2.

$$(\rho u)_x + (\rho v)_y = 0$$

$$\rho(u u_x + v u_y) + p_x = (\mu u_y)_y$$

$$\rho(u h_x + v h_y) - u p_x = -q_y + \mu(u_y)^2$$

$$\rho(u\, C_{i_x} + v\, C_{i_y}) = -(\rho\, C_i\, \hat{v}_i)_y + W_i$$

$$p = \left(\sum_i \frac{C_i}{\hat{M}_i}\right) \rho R T$$

$$h = \sum_i C_i \left[\int_0^T c_{p_i}\, dT + h_i^o\right]$$

$$C_i\, \hat{v}_i = -D_i \nabla C_i$$

$$q = -\lambda T_y + \rho \sum_i (C_i \hat{v}_i h_i) = -\lambda T_y - \rho \sum_i (h_i D_i C_{i_y})$$

$u = 0 \qquad$ @ $y = 0$	$u = u_e \qquad$ @ $y = \infty$

$$\dot{v} = v_w$$

$$h = h_w = \sum_i C_{iw} \int_0^{T_w} c_{p_i}\, dT + \sum_i C_{iw} h_i^o \qquad\qquad h = h_e = \sum_i C_{ie} \int_0^{T_e} c_{p_i}\, dT + \sum_i C_{ie} h_i^o$$

$$h_t = h_{tw} = h_w \qquad\qquad : \qquad\qquad h_t = h_{te} = h_e + u_e^2/2$$

$$T = T_w \qquad\qquad\qquad\qquad T = T_e$$

$$J_{iw} = -\rho_w D_{iw}(C_{iy})_w + \rho_w v_w(C_{iw} - (C_{iw})_-) \qquad\qquad C_i = C_{ie}$$

FIGURE 3

Theoretical Technique for Phase 1

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FIGURE 3

The theoretical study of the tip of the boundary layer is simplified
because the conditions outside this boundary layer are known and fixed and the
energy released at the surface or within the boundary layer is small. Although
important reactions are already taking place (see the effect of a simple catalytic
grid at the entrance of the reactor, for example), the concentrations of the main
species, at first, change only by negligible amounts, while traces of new and
important species (possibly chain carriers) appear. The problem is then reduced
to the solution of as many species equations for trace species as deemed neces-
sary to represent the chemical initiation reactions. All the flow properties,
including density, velocity, and temperature can be evaluated using available
boundary layer solutions for non-reactive flows thus decoupling the trace species
conservation equations from the equations for the main species and for mass,
momentum, and energy conservation. Even so, a large set of quasi-linear, coupled,
second-order partial differential equations for the trace species will have to be
numerically solved. The coupling derives from the boundary conditions at the
catalytic surface and from the gas phase reaction terms.

FIGURE 4 : STEADY COMBUSTOR

SWITCH

TRANSFORMER

ELECTRICAL CABLE FOR AIR HEATER

RELAY

TEMPERATURE CONTROLLER

115VAC

MESH SCREENS FOR FLOW STRAIGHTENING

SETTLING CHAMBER

SNOZZLE ASSEMBLY

MOTORIZED EXHAUST VALVE

TEST SECTION

DOLLY

DOLLY RAIL

FUEL & IGNITION

HEATER COIL ASSEMBLY

INTER-CHANGE-ABLE ORIFICE

PRESSURE CONTROLLER

PRESSURE GAGE (DOWNSTREAM)

PRESSURE GAGE (UPSTREAM)

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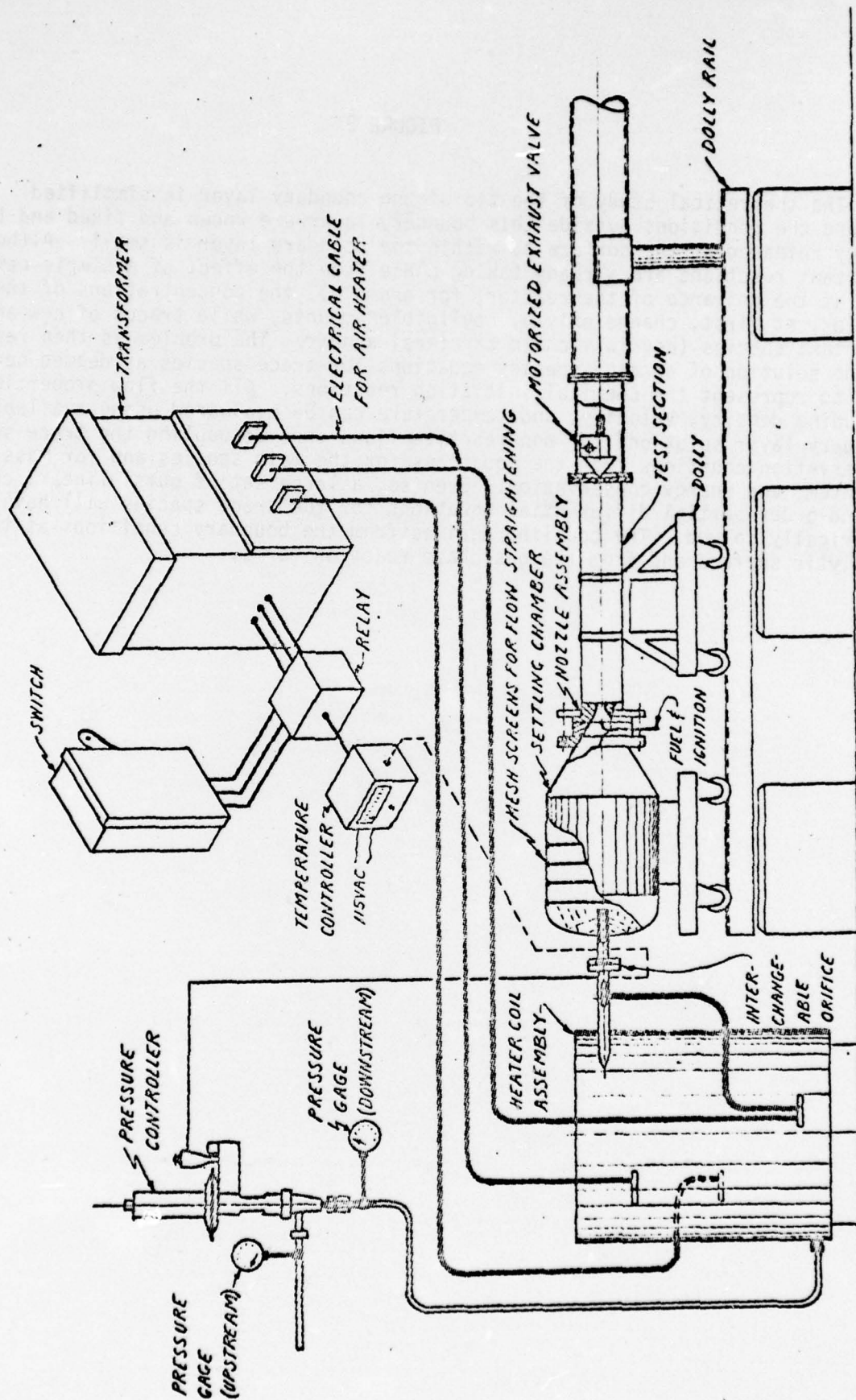
FIGURE 4

The experimental apparatus consists of a steady combustor. In the test section a thin wedge is inserted. The upper surface of the wedge, which is alined with the free stream reactant velocity,is coated with the catalyst. A boundary layer is initiated at the leading edge.

The main experimental tool is a continuous argon ion laser system to measure OH, HCO, N_2, O_2, CO_2, H_2O, CH_4, CO and other species in the reactive boundary layer along the catalytic surface. Resonance absorption in the near ultra violet will be used to measure OH concentrations. Resonance absorption in the visible and near infrared red will also be employed to measure HCO concentrations. The complementary fluorescence measurements will also be made if difficulties in accurately accounting for quenching can be overcome. The concentrations of N_2, O_2, H_2, CO_2, H_2O, CH_4 and CO will be measured using Stokes vibrational Raman scattering. Overlapping signatures of CO by N_2 may be a problem at the lower CO concentrations.

RESEARCH NEEDS IN COMBUSTION DIAGNOSTICS

By

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Introduction

Many combustion experiments requiring expensive, rather specialized instrumentation have not been performed. One reason for this is that funding agencies have viewed such proposed experiments as diagnostic development programs instead of combustion research. This view is slowly changing as the importance of combustion diagnostics is becoming more clearly recognized. It must be emphasized that combustion diagnostics, as of interest to the Air Force, is not an end product. It is one link in a chain of events in establishing a technology base from which high performance, low polluting combustors can be developed. The next section contains the background leading to the Air Force needs for combustion diagnostics.

Background

Development of turbojet engine combustors relies on the cut and try approach. It is supplemented with past experience, semiquantitative understanding of combustion processes, and numerous tests in which combustor performance characteristics are determined. This approach has been successful in the past but a development cycle of 3 to 5 years has resulted.

In the future, new design requirements will be placed on combustor developers. In the 1979-81 time period, commercial aircraft engines must satisfy Federal pollution regulations.[1] The Air Force plans to meet goals consistent with these regulations as long as military performance is not seriously degraded.[2] Additional Federal Regulations are anticipated for aircraft emissions into the stratosphere. Future combustors will also be required to burn liquid hydrocarbon fuels derived from tar sands, shale, and coal. These alternate fuels can have combustion characteristics significantly different from the present petroleum derived fuels. Undoubtedly, some combustor redesigns will be needed. Thus, the future requirements will be to improve combustor performance while at the same time burning alternate fuels and satisfying Federal pollution regulations. These requirements will seriously tax the combustion engineers and will undoubtedly greatly extend the combustor development cycle.

A better understanding of the fundamental processes occurring in combustors must form the technology base from which new design ideas and improved approaches for combustor development will result. An active integration of theory and experiment are essential for providing this base. Theories of processes occurring in combustors are being developed into

combustor models which could be of great value to future combustor design engineers. Combustor geometry, inlet conditions, and fuel properties provide input conditions for the models. Ideally, the models should accurately predict liner temperatures and detailed time averaged profile maps of specie concentrations, temperatures, and velocities inside and at the exit plane of the combustor. Specie concentrations of CO_2, CO, O_2, NO, NO_2, total hydrocarbons, and particulates are of interest. Combustor performance parameters and pollution levels would then be determined from the predictions. Combustor models are in the early stages of development and may never reach such a sophisticated level of prediction. While performance testing will always be essential in combustor development, the use of future models might significantly reduce the number of hardware modifications needed to develop combustors.

Research Needs

The intent of combustion diagnostics is to provide combustion data needed to establish a technology base which can be used in satisfying future combustor requirements. Hence, most of the diagnostics needs are driven by the combustion technology needs presented by other Air Force speakers at this meeting. The interested reader should refer to these needs. References 3 and 4 contain state-of-the-art surveys of the different diagnostic techniques and explore their potentials as combustion diagnostic tools. These are also highly recommended. Several of the more important needs are outlined in the following paragraphs.

Concentration, temperature, and velocity probes are routinely used in combustor development programs and by the combustion community in general. Because probes are inexpensive, simple, rugged, and easy to operate, they are and will remain important combustion diagnostics tools. In many applications they provide meaningful data. In other cases their results are questionable. For example, in the primary zone of combustors there are possible catalytic, incomplete quenching, and other sample perturbing effects which make it difficult to determine whether the extracted sample is biased.

Advances in laser technology have resulted in several optical techniques which might be applicable to combustion problems. Laser Doppler velocimetry (LDV), laser Raman scattering (LARS), fluorescence, coherent anti-Stokes Raman scattering (CARS), Mie scattering and Fraunhofer diffraction appear to be the most promising. However, these techniques have not been widely used in combustion studies. These techniques need to be employed in meaningful combustion experiments in which standard probing methods are not applicable. There is also a need for systematic evaluation of the measurement capabilities of probes and laser diagnostics in well defined combustion environments.

Providing meaningful data to check and aid in formulating combustion models is one of the most important applications of combustion diagnostics. Models for turbulent mixing, fuel evaporation and other important processes in combustors are being developed. Well designed experiments are needed to aid these model development efforts. Modelers should suggest experiments and where possible, work with experimentalists to design appropriate experiments and interpret data.

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AFAPL PROGRAM

AFAPL has a LARS system which has been hardened to operate in practical combustion facilities. A long term test program has been established to determine the measurement capabilities and limitations of this system. The system will be evaluated for making temperature and major specie concentration profile measurements at five different combustion test facilities located at AFAPL. The facilities are: (1) a test cell with an afterburning J85 engine, (2) a T56 combustor rig, (3) a ramjet combustor rig, (4) a F101 combustor rig, and (5) a combustion tunnel. Raman spectra of N_2, CO_2, and H_2O were obtained during preliminary measurements in the exhaust of an afterburning J85 engine. Raman measured temperatures compare favorably with temperatures calculated from gas sampling data.

A CARS system has been developed at AFAPL. The system has been used in the laboratory to make real time (20 nanosecond) measurements in a pure gas. If these tests continue to be encouraging, its capabilities as a combustion diagnostic tool for practical combustion systems will be evaluated.

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COHERENT   STRUCTURES   IN   TURBULENT   FLAMES

BY   LASER   ANEMOMETRY

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ABSTRACT

The main objective of the research program is to detect and measure coherent structures in turbulent flames.   The high-frequency response laser anemometer, which has been developed for velocity measurements in flames at Sheffield University, will be used simultaneously with high-speed movie visualization.   Experimental techniques which have, in the past, been used for studying coherent structures in turbulent flow fields without chemical reaction will be adapted and developed for studies of turbulent diffusion flames.   The presence of coherent structures, persisting for relatively long periods of time, will be shown to have an important influence on the formation, diffusion and destruction of pollutants in flames.

The laser anemometer at Sheffield University, powered by a 2 W argon ion laser and using a single particle counter for signal processing, has now been furnished with a real time clock.   Using the interface with a PDP8E computer, measurements are made of the velocity of each individual particle passing through the measurement control volume and recorded as a function of time. Examination of the time dependent variations of velocity allows detection of movements of coherent structures and conditional sampling.   Because of the extensive increases in kinematic viscosity of gases due to temperature increase across the flame, evidence is appearing that flows may be in the transitional regime rather than in the fully turbulent flow regime.

In diffusion flames, the presence of large coherent eddies results in burning being confined mainly to the interface, separating fuel and air. Physical models are being proposed implying the growth of non-burning, hot fuel-rich regions in the centres of vortices, in the initial region.   Mixing involves restructuring of eddies, accompanied by coalescence.   The model implies the possibility of the occurrence of regions of detached burning within the eddy.

Experimental studies on the combustion of air blast atomized liquid sprays have continued at the University of Sheffield. A laser anemometer with frequency shift, for reverse flow measurements, and a digital pulse counter was used for measurements of intantaneous velocity. Temperature was measured by miniature coated unshielded thermocouples and by suction pyrometer. Gas concentrations were measured in the flame by microprobes with analysis by gas phase chromatography. Droplet diameters were found to decrease in the initial region of the spray, due to secondary atomization, while further downstream, preferential vaporization of small droplets was found to lead to increases in mean diameter of droplet. Increasing the air flow rate through the atomizer resulted in significant reduction in droplet diameter throughout the spray length. Velocities in spray flames are significantly higher than in non-burning sprays as a result of acceleration caused by increased volumetric flow rates due to phase change and temperature increase. Concentration measurements show lack of oxygen in the central core of the spray, where carbon particles, carbon monoxide and hydrogen are formed.

Developments are being carried out on the laser anemometer system in order to simultaneously measure particle size and velocity. Calibration experiments have been carried out in which glass beads, with diameters between 20 and 300 microns have been traversed at known velocities through different sections of the fringe pattern produced by the crossed beams. The amplitude of scattered light, as detected by the photomultiplier, has been found to have a linear relationship with particle diameters under conditions of constant laser power and collecting angle. Particles not passing through the centre of the measurement control volume gave lower amplitude signals but they can be discriminated on the basis of measurement of visibility, as well as the areas under the envelope and pedestal of individual signals. Initial experiments are being made to measure droplet sizes and velocities simultaneously in spray flames. Attempts will be made to distinguish between small seeded particles, representing gas flows, and droplets with sizes up to 300 microns.

RAMAN SCATTERING MEASUREMENTS FOR
TIME- AND SPACE-RESOLVED DATA IN COMBUSTION SYSTEMS

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Many combustion problems of note for air-breathing propulsion engines involve the non-perturbing measurement of combustion parameters with stringent requirements on the experimental time and space resolution. For example, the determination of turbulent fluctuation information can provide such limitations, as can the measurement of detailed temperature pattern factors. Many of these requirements can be satisfied by measurement systems capable of providing resolution orders of magnitude of 1 µs and 1 mm^3 -- characteristics which can be provided by vibrational Raman scattering (VRS) techniques for temperature and composition measurements. Here, we will discuss the research objective of providing such VRS data for combustion systems and, in particular, the concomitant measurement difficulties and limitations. Other scattering measurement techniques will also be mentioned, particularly in comparison to VRS methods.

The basic approach for providing temperature information from VRS data involves relative intensity measurements of various spectral portions of the scattering profile from a major constituent, usually (but not necessarily) nitrogen in air-breathing systems. The method for density measurement for a particular constituent involves the observation of a significant part of its scattering signature relative to some standard, usually (but again not necessarily) the response from nitrogen in ambient air. These approaches

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to temperature and density determination will be outlined, and our recent progress in this area will be described.

Considerations based upon our results and those obtained in several other major laboratories have led us to the conclusion that significant prototype experiments utilizing VRS and providing 1 µs-1 mm^3 resolution or better are possible. Here, we will describe such a conceptual experiment, discussing briefly such considerations as laser choice and detection configuration. Emphasis will be placed on measurement problems. Examples of these are the limited rep rate that accompanies high-pulse-energy lasers selected for use with luminous combustion sources, and the limit to which an energetic laser pulse can be focused before interactions between the pulse and the combustion products perturb the VRS measurements. In discussing the latter problem, we will show that it establishes a trade-off between spatial resolution and measurement accuracy.

Our future plans for implementing VRS methods on combustion systems include: (1) detailed combustion subsystem experiments, focused primarily on measurement limitations (most prominently, on pulsed laser electrical breakdown studies carried out in flames); (2) development of unique measurement components, such as a novel method for measuring the VRS signals from two nearby spectral channels using the same interference filter; (3) "bench-top" combustion experiments, such as the measurement of instantaneous temperature values in a turbulent coaxial hydrogen-air diffusion flame already well-characterized by laser velocimetry (LV) data; and (4) the design and execution of a large-scale combustion measurement program on coaxial diffusion flames involving simultaneous temperature and composition data from VRS, velocity data from LV, and additional probe data where required (such as sampling probes for minor constituents).

The material upon which this presentation will be based is

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AIRCRAFT FIRE PROTECTION TECHNOLOGY

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The primary objective of AFAPL fire protection program is to develop effective, low cost, low penalty, and maintenance-free fire/ explosion prevention and suppression systems for aircraft safety and combat survivability. This requires conducting research efforts to identify potential fire and explosion hazards under both natural and combat environments, to determine flammability properties of jet fuels, engine oils, and hydraulic fluids, to investigate combustion dynamics under various flight environments, and to investigate various active and passive protection techniques. This paper will review briefly AFAPL research efforts in these areas and will present more detailed discussions on selected current and future programs. Some of the specific programs to be discussed are: fuel tank ullage modelling, fuel vapor ignition by laser, fuel spray/mist generated by a projectile, flame suppression by fuel-wetted reticulated foam, and effects of air flow on confined fuel fires. In discussing these programs, emphasis will be placed on identification of combustion related problems which need better fundamental understanding to enable future improvements in aircraft survivability from fire and explosion threats.

IGNITION, COMBUSTION, DETONATION, AND

QUENCHING OF COMBUSTIBLE GAS MIXTURES

R. Edse

Detonation induction distances, wave speeds, and pressures in the build-up region have been determined in a 6.4 m long, 5 cm internal diameter cylindrical tube for hydrogen-air mixtures at an initial pressure of one atmosphere and initial temperatures ranging from 123K to room temperature. The results of these measurements showed that the induction distances are greatly reduced when the temperature of the unburned gas is lowered. This decrease occurred in spite of the decrease of the normal flame propagation rates with temperature. The flame propagation rates were measured over a wide range of temperatures.

The flame propagation rates of hydrogen-air mixtures were also measured in unconfined clouds by high speed motion pictures and strip film photographs with rotating drum cameras. According to these experiments the propagation rates increased with the diameter of the clouds.

Two new detonation tubes are being set up for the investigation of the parameters leading to quenching of deflagrations and detonations. The effects of the arrestor configuration and material on both the flame and the shock wave are to be determined. Some of these studies will be made in vertical tubes to study the effect of buoyancy on the imitiation of detonation and on the efficiency of a flame arrester.

Equations have been developed and several examples have been worked out to determine the effects of mixing on the thermodynamic and gasdynamic properties of sub and supersonic flows with and without chemical changes.

IGNITION OF FUEL SPRAYS
BY INCENDIARY METAL PARTICLES

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As a projectile penetrates an aircraft skin and the fuel tank wall behind it, two types of fire hazards are possible. The first is fire in the dry bay area where a flammable atmosphere, created through vaporization of the fuel spray squirting out of the fuel tank rupture, is ignited by the incendiary metal particles abraded off the aircraft skin by the penetrating projectile. The second is fire in the ullage where a flammable gas mixture already exists and is ignited either by the fast-moving hot projectile or the incendiary metal particles. Whereas the ignition of a flammable mixture by a hot projectile has been treated (Sharma and Sirignano, 1971), little information exists when the ignition sources are incendiary metal particles. The present project is a theoretical-experimental effort to supply the needed information for the servivability/vulnerability community.

The program is only one month of age so that little progress can be reported, but an approach plan can be discussed. The research will be conducted in three phases. In the first phase the ignition of a single metal particle upon receiving an ignition stimulus will be studied. Obviously, if the ignition of metal particles can be suppressed, the likelihood of flammable mixture ignition can also be drastically reduced. Whereas various techniques for metal particle ignition exist, for example those of thermal heating, abrasive grinding, and exploding wires, we have adopted the pulsed laser irradiation technique of Wilson and Williams (1971) since (i) the particle size under testing

can be accurately controlled; (ii) the gas environment is cold and is not altered by the ignition process; and (iii) the ignition stimulus is instantaneously applied and withdrawn, hence simulating the frictional heating the particles are subjected to upon being abraded from the metal sheet. The detailed design of the apparatus is underway. Theoretical models for ignition will also be formulated, particularly for aluminum and titanium. Various possible ignition mechanisms (e.g. surface versus gas-phase reactions) will be explored, possibly using the systematic approach of asymptotic analysis in the limit of large activation energies.

In the second phase the ignition of a flammable mixture by an incendiary metal particle will be studied. The same experimental set-up will be used except now a volatile hydrocarbon vapor, consisting of blends of pentane and hexane to simulate the JP-4 fuel, is introduced into the O_2 / inert atmosphere. The ignitability of the system will be studied for given mixture strength, mixture temperature, and particle size. A theoretical model for the ignition process will also be formulated.

The last phase will involve studying the ignition of a fuel spray by an incendiary metal particle. The basic experimental apparatus will be modified to allow for a steady flow of mono-disperse spray, at different stages of vaporization, past the test section. Theoretically the ignition criteria from the second phase will be combined with an analysis for spray vaporization to provide overall ignition criteria for the spray situation.

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